1958

Mechanical ventilation for moisture control in farm-stored grain

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MECHANICAL VENTILATION FOR MOISTURE CONTROL IN FARM-STORED GRAIN

by

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A Thesis Submitted to the
Graduate Faculty in Partial Fulfillment of
The Requirements for the Degree of
MASTER OF SCIENCE

Major Subject: Agricultural Engineering

Signatures have been redacted for privacy

Iowa State College
1958

1126 Eng

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INTRODUCTION

A phenomenon which has been known to exist in the field of grain storage for some time has recently become increasingly important. This phenomenon is that of the migration of the moisture in a bin of grain from one portion of the bin to another. This is caused by convection currents of air which are present in the grain and are due to the temperature differential between one portion of the bin and another. The temperature differential is due to the mass of grain usually found in a bin. In the fall and early winter, the portions of a bin near the outer surfaces may be getting quite cool while that nearer the center of the bin may still be very near the maximum temperature achieved during the summer months. This temperature difference tends to cause the interstitial air to have a downward movement near the outer surfaces of a bin and a corresponding upward movement near the center.

As the air moves through the warm portion, it has a lower vapor pressure than the grain. This tends to cause the amount of moisture in the air to increase with a corresponding decrease in the amount in the grain.

As the air nears the surface of the grain, it again comes into a region which is cool. This time, the vapor pressure of the air is greater than that of the grain, resulting in an increase in the moisture content of the grain with the corresponding decrease now occurring in the air. A complete description of moisture migration, with accompanying illustrations, is given by Holman and Carter (3).

The initial effect of moisture migration is this increase in the moisture content of the grain at or near the surface of the grain mass. This increase, if allowed to continue, can reach as high as 24 per cent in soybeans (3) and 30 per cent in corn (6), even though the initial moisture content at the beginning of the storage period was considered to be at a level such that grain spoilage would not be anticipated.

The detrimental effects of moisture migration can be controlled by the forced movement of air through the mass of grain. This has the effect of creating a more nearly uniform temperature throughout. In large bins, this movement is effected by the use of perforated pipe laid on the bin floor. Air is pulled downward through the grain, into the pipe, and exhausted into the atmosphere by a power-driven fan. In smaller bins, such as those commonly found on farms, it has been found (1) that an air duct made of 5-inch galvanized stove pipe with two lengths of perforated pipe, and a small, 80-watt, electric fan can be effectively used in the control of moisture migration. The pipe is inserted from the top-center of the bin, vertically, into the grain. As the pipe is pushed into the grain mass, the grain is removed from within the pipe such that when the pipe is installed, there has been provided an air duct into the center portion of the bin. When the fan is attached and air exhausted from the duct, at a time when the weather is cool, a process of cooling the grain takes place.

Since the amount of pipe used for this on-the-farm grain-cooling system is somewhat governed by whatever is commercially available, it was felt that it would be worthwhile to study the effects of varying the components of this system to determine what effect this might have on the amount of cooling which would be accomplished.

Other methods of control of moisture migration may be possible; however, the use of the above method is quite widespread and it is believed that a more thorough understanding of this method would be more desirable, at present, than to try to determine other methods of control.

REVIEW OF LITERATURE

The effects of moisture migration have been known to farmers and grain men for some time. They have known that damp grain can be found on the surface of bins of grain in late winter. The cause of this moisture migration has also been known for some time. Holman and Carter (3) give a description of this phenomenon with sectional views of bins showing the temperature distribution in bins at different times of the year, along with the moisture content of the grain within the bin. They also note that,

> The amount of moisture movement in the upper layers (of a bin) has been reduced in experimental bins by cooling the corn in the bin by forced ventilation with cold air during a cold period in the fall or early winter.

This circular further states, "It is questionable, however, that these benefits (from cooling) are sufficient to justify the cost of power ventilation." This statement being made after stating that, "The amount damaged (in each bin) . . . is generally not over 5 to 20 bushels." This damage occurring in a 2000-bu bin.

In November, 1951, Robinson, Hukill, and Foster (6) published their findings on the effect of ventilation on migration of moisture in large bins. This article covered studies which had been made on 25,000-bu, quonset-type, buildings.

Cooling was accomplished with a tunnel arrangement on the floor of the bin with air being exhausted from the tunnel, as described above in the Introduction. Charts were presented which showed moisture accumulation in the surface layers of grain, both in ventilated and unventilated bins. In a section entitled "Previous Investigations," there were described bins (2740-bu, 18-ft diameter) where spoilage had been observed to amount to 45 to 50 bu in each bin, occurring in an area 10 ft in diameter and 6 to 9 in. deep in the top-center of the bin, which had been caused by moisture migration.

It is not the purpose of this manuscript to cover the economic aspects of grain cooling in preventing moisture migration. Factors have entered into this problem which make the differences in the amount of spoilage, as given by the authors above, less significant. These other factors are federal regulations governing grains in storage and under loan to the government.

The portion of the regulations (9) which applies to the storage of grain on farms and which is pertinent to the problem covered by this manuscript is:

> Credit will be given (for delivery of corn under the extended reseal program) at the applicable settlement value according to the grade and quality for the total quantity eligible for delivery . . . .

The portion of the government regulations (10) which applies to the storage of grains in warehouses is:

> The warehouseman, at his own expense, shall take all necessary steps to keep all of the grain which is stored in the warehouse (whether commingled or identity preserved) from going out of condition and shall condition any such grain which is out of condition or in danger of becoming so, to the extent he is equipped to do so, and if after such care and conditioning, the grain cannot be prevented from going out of condition, the warehouseman shall immediately notify Commodity (Credit Corporation) in accordance with the provisions of section 10 (C) A hereof. Lack of equipment shall not excuse the warehouseman from liability for deterioration occurring prior to such notice.

As can be seen from the above-quoted regulations, it is important that grain can be kept in condition in order to qualify for government loan and storage benefits.

Hukill (4) reports on results of cooling grain by two methods. The first method was by insertion of a pipe into the grain near the bottom of a bin. This pipe being pushed horizontally to the center of the bin. Air was then drawn out by a 25- to 30-hp fan until the grain was cool and convection halted. This method was found to be unsatisfactory due to the difficulty of insertion of the pipe. It was also expensive due to the equipment required. The rate of cooling was not as rapid as was expected, and was believed to be due to a larger proportion of the air coming from the outer portions of the bin where the natural flow of the air already tended to be downward.

The second method was very similar to that described in the Introduction under ventilation of farm-size bins. The results of this second method, which showed considerable promise, are shown in Table 1.

Table 1. Average moisture content of corn from top foot of grain at center of bins with and without ventilation

Date	30-ft round bins		18-ft round bins	
	Non-ventilated	Fan ventilated	Non-ventilated	Fan ventilated
Feb. 1, 1953	17.1(10)	14.0(21)	19.2(4)	14.3(5)
March 15, 1953	22.0(10)	14.4(22)	18.8(4)	15.1(5)

Note: The numbers in parentheses are numbers of bins contributing to the average moistures shown.

Herum (1) conducted a series of tests which had as their objectives,

> . . . to determine if mechanical ventilation is a satisfactory means of controlling moisture migration and insect infestation in farm stored grains; to determine the minimum bin size in which mechanical ventilation is beneficial; and to determine which methods and equipment for mechanical ventilation will most effectively produce the desired results.

The conclusions reached were that, "A single year of study of moisture migration and its control in farm storage is not adequate to justify definite and specific conclusions."

Other publications are extant which are primarily concerned with grain conditioning by the use of air; however, these do not seem to add anything to the problem covered in this manuscript, or else they cover some special situation which does not apply here.

ANALYSIS OF THE PROBLEM

In an analysis of a problem, it is necessary to determine what the components of a system are which can possibly be varied and would produce some variation in the results.

In the problem described by this manuscript, the variables which could possibly produce some significant change in the effects on the surrounding grain are:

1. Amount of air flow
2. Length of solid pipe
3. Length of perforated pipe
4. Diameter of solid pipe
5. Diameter of perforated pipe
6. Ratio of open area to total area of the perforated pipe
7. Type of grain surrounding the pipe

At the present time, the above factors have been chosen, to a certain extent, by what was commercially available. It was felt that the next logical step was to examine them individually to determine each one's effect on the cooling of grain. Once the individual effect of each is known, combinations of them can be made which will give predictable results.

The procedures and results reported by this manuscript focus their attention on two of the above seven components.

These two components are the length of the perforated pipe and the length of the solid pipe.

The system covered here is simply a pump connected to a duct which extends downward into a porous medium. At the bottom of this duct is a length of perforated pipe used as a means of allowing the interstitial fluid in the porous medium to enter the pipe without allowing entry of the porous medium itself. This description is given in this manner for a very specific reason. It will also fit an ordinary well used to obtain water from below the surface of the ground. The analogy is an important one since some very useful work has been done on well screens by Petersen, Rohwer, and Albertson (5). In the work cited, an equation for well screens is derived which gives

$$\frac{\Delta h_{pz}}{Q^2/A^2g} = \frac{\cosh\left(\frac{CL}{D}\right) + 1}{\cosh\left(\frac{CL}{D}\right) - 1} \tag{1}$$

Δh_{pz} = difference in piezometric head between inside and outside of a well screen, ft of fluid flowing

Q = quantity of flow parallel to the screen axis past a given section inside the well screen, cfs

A = cross-sectional area of the duct, sq ft

g = acceleration of gravity, ft/sec/sec

L = length of the perforated section of the well screen, in.

D = diameter of the well screen, in.

$C = 11.31C_cA_p$, dimensionless

C_c = coefficient of contraction

A_p = per cent of the total area of a well screen that is open area

This equation presents a dimensionless parameter $\frac{\Delta h_{pz}}{Q^2/A^2g}$ as a function of another dimensionless parameter $\frac{CL}{D}$. Petersen plots the theoretical curve of the two dimensionless parameters given in equation 1. This theoretical curve is reproduced in Figure 1.

"As shown by the theoretical curve, the loss coefficient $\frac{\Delta h_{pz}}{Q^2/A^2g}$ becomes nearly constant when the hyperbolic cosine of $\frac{CL}{D}$ is large, so that the plus or minus 1 is insignificant. The curve becomes asympototic to a loss coefficient equal to unity, but for practical purposes, the loss coefficient equals unity for all values of $\frac{CL}{D}$ greater than 6." (5, pp. 8-10) Thus, there is no change in loss through a well screen, no matter what its length, as long as $\frac{CL}{D}$ is 6, or greater. This value was verified in a laboratory experiment.

Using the dimensions of the apparatus used in this investigation:

L = unknown length of perforated pipe necessary, in.

D = 5 in.

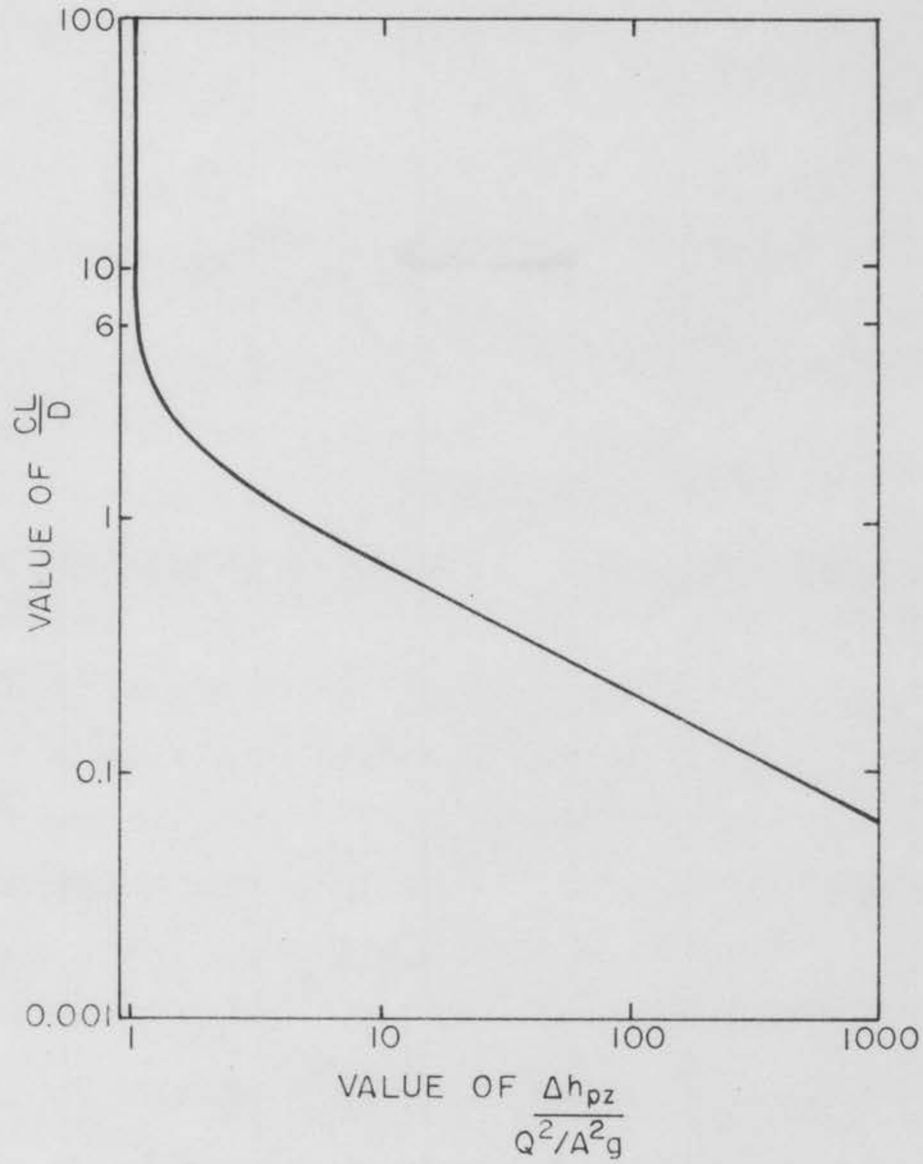

Figure 1. Loss coefficient as a function of $\frac{CL}{D}$

$A_p = (0.40)(0.40)$*

$C_c = 0.60$ (assumed)

Then,

$$\frac{CL}{D} = 6 \tag{2}$$

$$L = \frac{6D}{C} \tag{3}$$

$$= \frac{6D}{11.31A_pC_c} \tag{4}$$

$$= 27.6 \text{ in.}$$

On a trial basis, then, the length of perforated pipe need not exceed a length of 27.6 in. depending on the validity of the well-screen analogy.

Figure 1 also provides a simple means of solving for the head loss through a well screen, once the flow is known. It is now possible to calculate a $\frac{CL}{D}$ value for each system used in the work reported by this manuscript. This value can then be used to calculate a value for the head loss through each aeration system which will be used in further analysis of the problem. The calculated values of $\frac{CL}{D}$, using values given above, are shown in Table 2. By use of Figure 1, values for $\frac{\Delta h_{ns}}{Q^2/A^2g}$ can be found which are also given in Table 2. Some preliminary trials show that the flow is approximately 56 cfm.

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*The first 0.40 represents the per cent open area of the perforated pipe, the second 0.40 represents the per cent void space in corn (11).

Using this value, it is now possible to calculate the Δh_{pz} for each length of perforated pipe. This is the Δh_{pz} value given in Table 2.

Table 2. $\frac{CL}{D}$ and $\frac{\Delta h_{pz}}{Q^2/A^2g}$ values for 1-ft, 3-ft, and 6-ft sections of perforated pipe used in vertical-duct ventilators

Item	1 ft	3 ft	6 ft
$\frac{CL}{D}$	2.61	7.8	15.6
$\frac{\Delta h_{pz}}{Q^2/A^2g}$	1.6	1	1
Δh_{pz}, in. water	0.00144	0.0009	0.0009

It is desired to estimate the amount of air flow that can be expected from the vertical-duct systems used here. The method which will be used in this estimate is to determine the head loss of the air as it moves through the grain, through the perforations, and into the duct.

Shedd (8) provides a means of determining head loss in flow of air through grain if the rate of air flow and the path of the air flow is known. Since the air flow in the situation reported here is radial, Shedd's information is not directly applicable. The method of approach which was used was to assume that the air flowing into the system had a certain pattern. The system using 1 ft of perforated pipe is shown in Figure 2 and will be used to illustrate the method used for estimating the flow from all systems.

In order to use this method, it was necessary to have an estimate of the pressure within these ducts. For this reason, a reading was made on a system having 1 ft, one having 3 ft, and one having 6 ft of perforated pipe. These values are given in Table 3.

Table 3. Measured values of differential pressures within the vertical-duct ventilators

Item	Length of perforated section		
	1 ft	3 ft	6 ft
Differential pressure, in. water	0.18	0.08	0.05

It was assumed that the pressures given in Table 3 were acting over the entire surface of all three of the systems. This would facilitate making the assumption that the air is drawn equally from all directions around the perforated pipe. This means that any surface generated around the perforated pipe which is at every point an equal distance from the nearest part of the perforated pipe has an equal amount of air flowing through a unit of area. The thickness of grain through which this is happening would remain unknown; however,

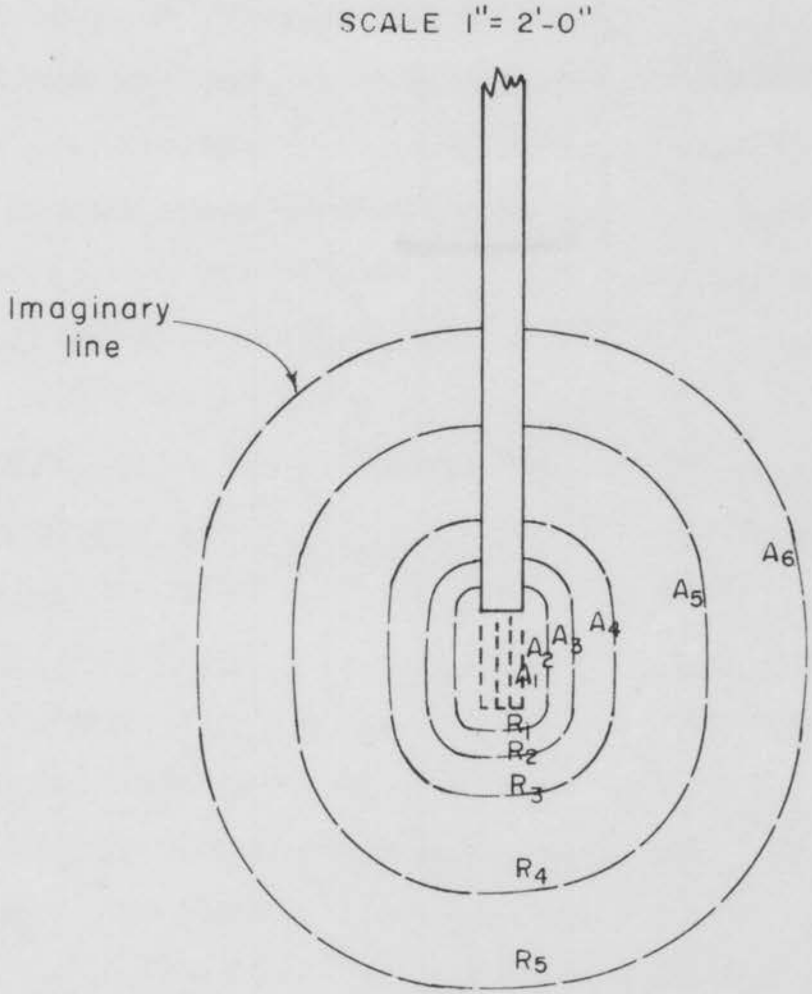

Figure 2. Drawing of a system using a 1-ft length of perforated pipe showing imaginary lines which were used to determine the pressure drop through the grain as the air approaches the duct

it can be assumed that at some distance from the perforated pipe, the change in pressure per unit depth would become so small, it could be assumed to be zero.

Since this problem is concerned with radial flow, the nearer the air comes to the pipe, the greater will be the flow per unit area; therefore, the grain surrounding the duct is divided into a series of regions, each region consisting of portions which are equidistant from the perforated pipe. These divide the grain into shells which are small enough that each can be dealt with separately as a portion of grain having an air flow which is uniform throughout its depth. In Figure 2, the lines A_1-A_6 represent the lines equidistant from the perforated duct. R_1-R_5 represents the shells of grain. The surfaces A_1-A_6 are made up of geometrical figures; therefore, their areas can be calculated. By assuming an air flow, the air flow per unit area can be determined at each surface. From Shedd's chart (8), the head loss per ft of depth can be found for each point, and the average value found for each region. This value, multiplied by the thickness of that region, will give a value for the total head loss through that particular region. The air flow that would be expected from any of these systems would then be that assumed air flow where the sum of all the calculated head losses plus the loss through the perforated pipe equalled the measured pressure given in Table 3.

In the determination of the values, the points representing the assumed air flows and their corresponding calculated static pressures were plotted as a curve. The air flows corresponding to the measured static pressures, as read from these curves, are the values given in Table 4.

Table 4. Estimated values of air flow from vertical-duct ventilators

Item	Length of perforated pipe		
	1 ft	3 ft	6 ft
Estimated air flow, cfm	65	93	124

Since values for the head loss through the perforated pipe are so small and since there is no evidence available to determine the validity of the well-screen analogy, the head loss through the perforated duct was taken to be, essentially, zero.

It is to be noted from Table 4 that all three of the values are substantially higher than the value of 56 cfm which was measured in a preliminary test.

The above analysis considered that a static pressure was acting over the surface of the perforated duct which was everywhere the same. If it is considered that at the lower end of any of the perforated ducts reported here, there is a small differential pressure, air will flow in. As this air moves along the duct, more air will be entering due to this differential pressure. As more air enters, the velocity increases. Increasing the velocity increases the velocity head, which causes a decrease in the static pressure, causing the air to enter at a still greater rate. Thus, the static pressure varies along the length of the perforated duct rather than being a constant, as assumed. It would be desirable to determine if this would be a significant factor in this analysis. To determine its significance, it should be determined what the total velocity head is and compare that value with the total static head which was measured.

A value of 56 cfm, flowing in a 5-in. diameter duct gives an average velocity of 412 fpm. This is equivalent to a static pressure of 0.01 in. of water. This value would be significant in the case of the systems having 3-ft and 6-ft of perforated pipe since their total measured static head was 0.08 and 0.05 in. of water, respectively. However, in the case of the 1-ft perforated section, the importance of the velocity head is less since the total static head developed here was measured as 0.18 in. of water. The significance here is that as shorter and shorter lengths of perforated pipe are used, the calculated values of air flow will approach the measured values and give more reliable results since the variation in static pressure from one end of the perforated pipe to the other will decrease as the duct length decreases.

In further analysis of the vertical-duct ventilators, it is noted that nothing has been determined about the effect of the depth at which the perforated pipe is placed on the quantity of air flow. In estimating the quantity of air flow, account was made of the effect of pressure drop out to a point 3 ft from the perforated duct. See Figure 2. At this point, for the 1-ft section, the differential pressure would be 0.0016 in. of water per ft depth. Considering the depth of grain in most farm-type bins, this value was assumed to be negligible; therefore, beyond the 3-ft point, the pressure could be considered zero.

The grain in a bin which is being aerated is subjected to continually-varying conditions. The temperature of the air being drawn through the grain is a continual variable. In addition to this, there is the problem of the convection currents. These currents are due to the temperature differential, as pointed out before; however, they produce one additional factor. As the outside air temperature is continually varying from one season to the next, the differential temperature is also varying. This causes the amount of air flowing by convection to vary. Since the vertical-duct ventilators will always choose their source of supply to be that which presents the least resistance to flow, if convection is present, the ventilators will have a supply of air forced upon them due to the upward movement of air in the center by these convection currents. Therefore, if this convection is varying in intensity, the air which is being exhausted by the fan will be coming from a continually-changing combination of sources. Therefore, the portion of a bin which is affected by these vertical-duct ventilators will change as the conditions causing convection change.

INVESTIGATION

The investigation was carried out in three phases. The first phase was that where the grain in a bin is cooling off as in the fall of the year. The second phase was that where the grain in a bin is warming up as in the spring of the year. The third phase was that of measuring air flow from the various combinations of vertical ducts. In the presentation of the three investigations which were carried out, each will be taken up separately. The method of procedure, results, and discussion of results of each are presented separately, with a general presentation of results given in the Summary.

Investigation of the Effectiveness of Vertical Ducts With Continuous Cold-Weather Operation

Method of procedure

Although the aeration units are designed for use in bins such as those found on farms, the experimental work was carried out in the quonset-type structure 40 ft wide by 125 ft long, shown in Figure 3. This was done for three reasons. A large bin such as this would permit placing all the fans to be used in one bin which would facilitate the gathering of data. A single bin gives one which has been filled at one

Figure 3. Quonset-type structure where investigations were conducted

time, giving grain which has more nearly the same characteristics. Also, it was desired that the fans be placed in a mass of grain large enough that the effects of the cold air on the walls would have an effect on the center portions of the grain which would be small relative to the effect of the aeration. Thus, the patterns obtained would not be similar to those where the bin walls had some effect on the flow.

The duct used was made of ordinary galvanized stove pipe with a 5-in. diameter. The perforated portion has a 40-per cent open area as previously described in the Analysis of the Problem. The fans which were used in all of the tests had a rating of 0.70 amp and delivered approximately 80 cfm when they were operated in the open air.

The pipe sections were assembled with sheet-metal screws and all joints were taped to prevent entry of air any place other than through the perforated pipe. The fan which was attached to 6 ft of solid pipe and 3 ft of perforated pipe is shown in Figure 4 as an example of those used. The black line around the pipe near the fan shows the point where the surface of the grain will be when the unit is installed.

Each of these systems was placed at an interval of 10 ft in the bin. In all cases an extra length of pipe was used to elevate the fan above the surface of the grain. The pipes were installed by pushing them down from the surface of the bin and withdrawing the grain from the inside of the pipe

Figure 4. Fan and pipe assembly ready for installation in the bin

Figure 5. A fan installation showing thermocouple cables

by means of a household vacuum cleaner as described by Hukill (4).

In this portion of the study, ten fans were used with as many different combinations of solid and perforated pipe. The data to be used in evaluating the effect of the various combinations were the temperatures of the grain surrounding each installation. The temperatures were measured by means of cables inserted in the grain at 24-in. intervals away from the pipe. Each cable had a number of thermocouples spaced at either 12 in., 18 in., or 24 in. with the spacing extending from the surface of the grain, downward. Table 5 presents the fan and pipe combinations which were investigated with the thermocouple spacing which was used on each cable. Figure 5 shows a fan installation with the thermocouple cables installed. All temperatures were measured using a Rubicon potentiometer accurate to $\pm$ 1°F.

Figure 6 is a cross-sectional view of fan-installation I, as given in Table 5. It should be noted that the grid formed by the thermocouples is at one side of the fan only. It was assumed that the patterns of flow around the installation are essentially the same in all directions; therefore, whatever was shown by the results could be assumed to be representative of any cross-section of the installation.

The bin which was used for these experiments was filled with corn to a depth of 16 ft and had an aeration duct run-

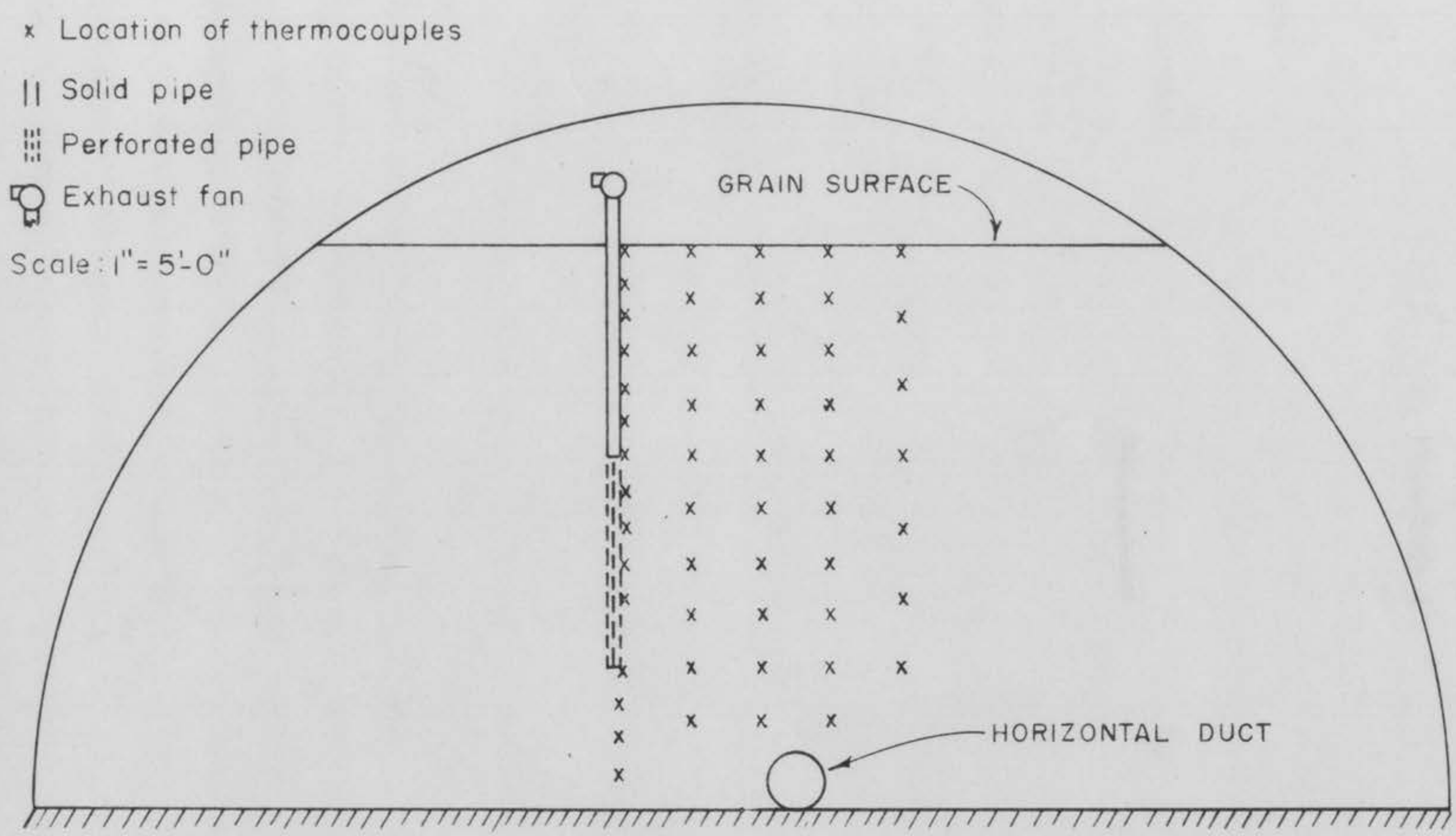

Figure 6. Cross-sectional view of the bin at fan-installation I

Table 5. Pipe and thermocouple-cable combinations used in the investigation of the effectiveness of vertical ducts with continuous cold-weather operation

Item	Pipe designation									
	A	B	C	D	E	F	G	H	I	J
Length of solid pipe, in.	48	48	72	48	72	72	96	96	72	96
Length of perforated pipe, in.	0	12	0	36	12	36	12	36	72	72
Cable spacing, in.	12	12	24	24	24	24	24	24	24	24
Thermocouple spacing, in.										
Cable 1	12	12	12	12	12	12	12	12	12	12
Cable 2	24	24	24	24	24	24	24	24	24	24
Cable 3	24	24	24	24	24	24	24	24	18	18
Cable 4	24	24	24	24	24	24	24	24	18	18
Cable 5	24	24	24	24	24	24	24	24	18	18
Cable 6	--	24	--	--	--	--	--	--	--	--

ning horizontally along the floor. The owner operated his own fans by connecting them to this horizontal duct. These fans were operated until every part of the bin was at a temperature of 60° F, or below. This was done as a precautionary measure since there was a possibility that the fans used here would not prevent some damage to the stored corn due to moisture migration. It was judged that this would not be sufficient cooling to hinder the purposes for which this experiment was designed. After completion of this partial cooling, the fans were disconnected and the duct was sealed with a metal lid at each end. This is the circular apparatus being held by a diagonal piece of wood at the bottom, and near the center, of the end of the bin shown in Figure 3.

Temperature readings were to be taken at regular intervals throughout the winter season, the time interval of one week chosen as being sufficient.

The fans were not started into operation until November 22. Prior to this time, it was believed that there would not be a great enough temperature differential between the temperature of the grain and that of the outside air to produce any temperature changes which would show the effectiveness of the various systems.

The visible result of moisture migration is the increase in the moisture content of the grain near the top surface of a bin; therefore, a measure of the complete effectiveness of aeration is to measure the grain moisture content to determine if there is any variation in the grain moisture surrounding the fan installations. Since the grain has already been aerated, to some extent, through the use of the horizontal tunnel which is already installed, any variation would not be the true change which would occur naturally in a bin. Thus, the effect of these fans in the prevention, or lack of it, of any accumulation of moisture in the surface region of the bin will only be relative and cannot be thought of as being directly applicable to another bin which has had different treatment. Also, small changes in moisture content of grain can occur, even in the absence of convection currents; therefore, small changes do not tell the effectiveness of aeration in preventing moisture migration since the relative amount of increase due to convection and to other causes would be unknown.

A set of grain moisture samples was taken at each fan installation. Four samples were taken with a 10-compartment grain probe, giving a sample of the moisture content of the grain in the top 6 in. of the bin, in the second 6 in. below the surface, from the region which is from 1 to 2 ft below the surface, and one sample 4 ft below the surface. Six sets of these samples were taken at each fan, one next to the pipe and the rest at intervals which are the same as those of the thermocouple cables and in the same plane. The moisture content of the samples was obtained by use of a Tag-Heppenstall Moisture Meter.

Results

The results of the study on the effectiveness of these various combinations are to be shown as a series of temperatures taken in a grid pattern about each installation as given above. These fans are used in continuous operation over relatively-long periods of time. For this reason, the change from one week to another has less importance than the change which will occur over longer periods of time.

The results are presented in pictorial form in Figures 7 through 23. These drawings present a cross-sectional view at each fan installation which shows the fan and lines of constant temperature around each duct system for the months indicated. These lines of constant temperature were drawn by averaging the individual readings for each month, plotting them to scale, and drawing in the lines shown. This averaging method overcomes much of the effect of any errors in reading temperatures and gives comparisons of changes of temperatures over longer periods of time, both desired objectives.

The results of the grain moistures at each point are given in tabular form in Table 6.

Discussion of results

A discussion of the results which are determined by this portion of this manuscript must be general rather than specific. Since conditions are constantly changing, anything which might be true at one place would very probably be changed at another. For this reason, the discussion must confine itself to how things are changing from time to time and what are the characteristics which appear in such a way that they can be applied in general cases.

Figure 7. Average monthly temperatures around fan A, the installation having 4 ft of solid pipe

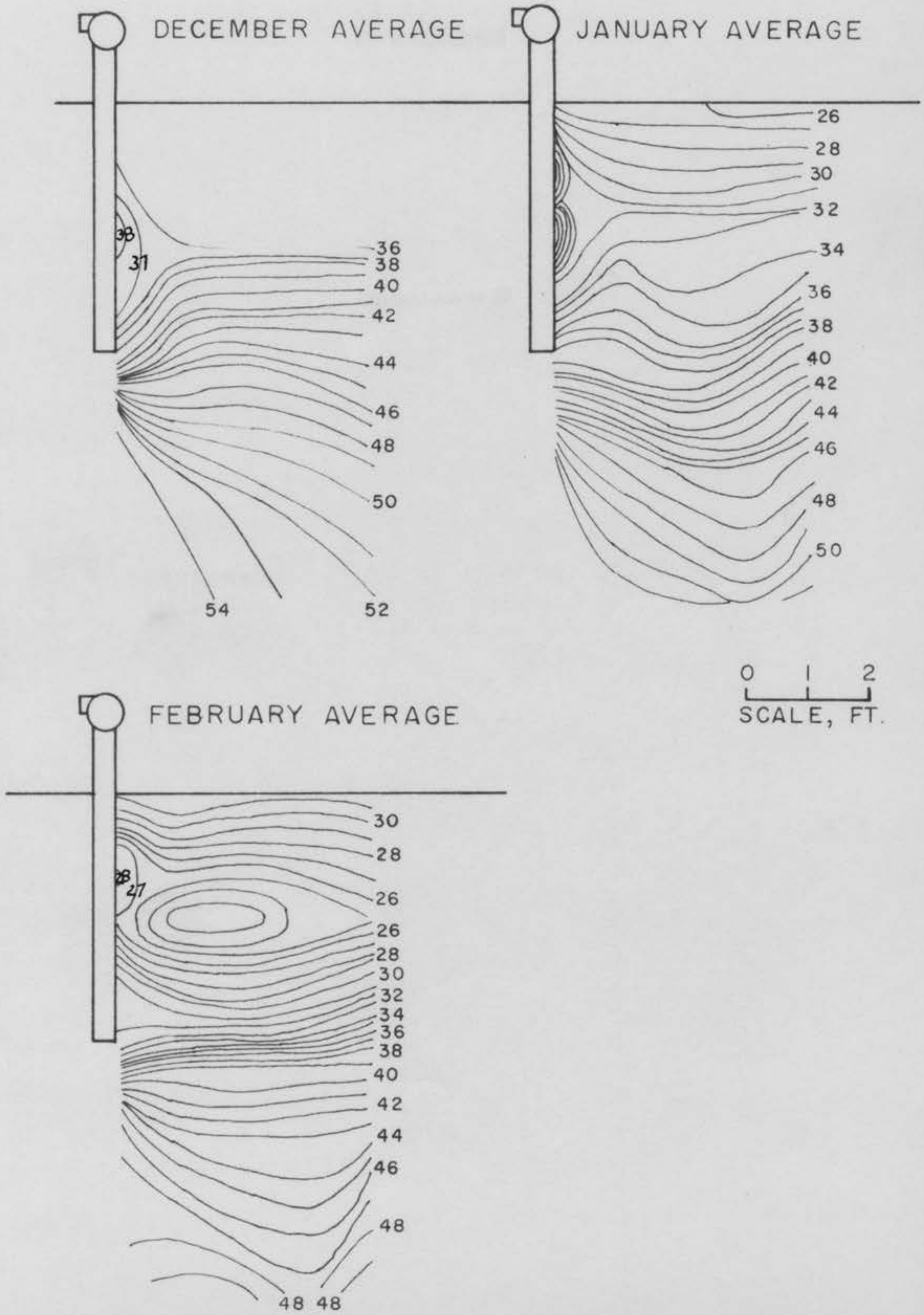
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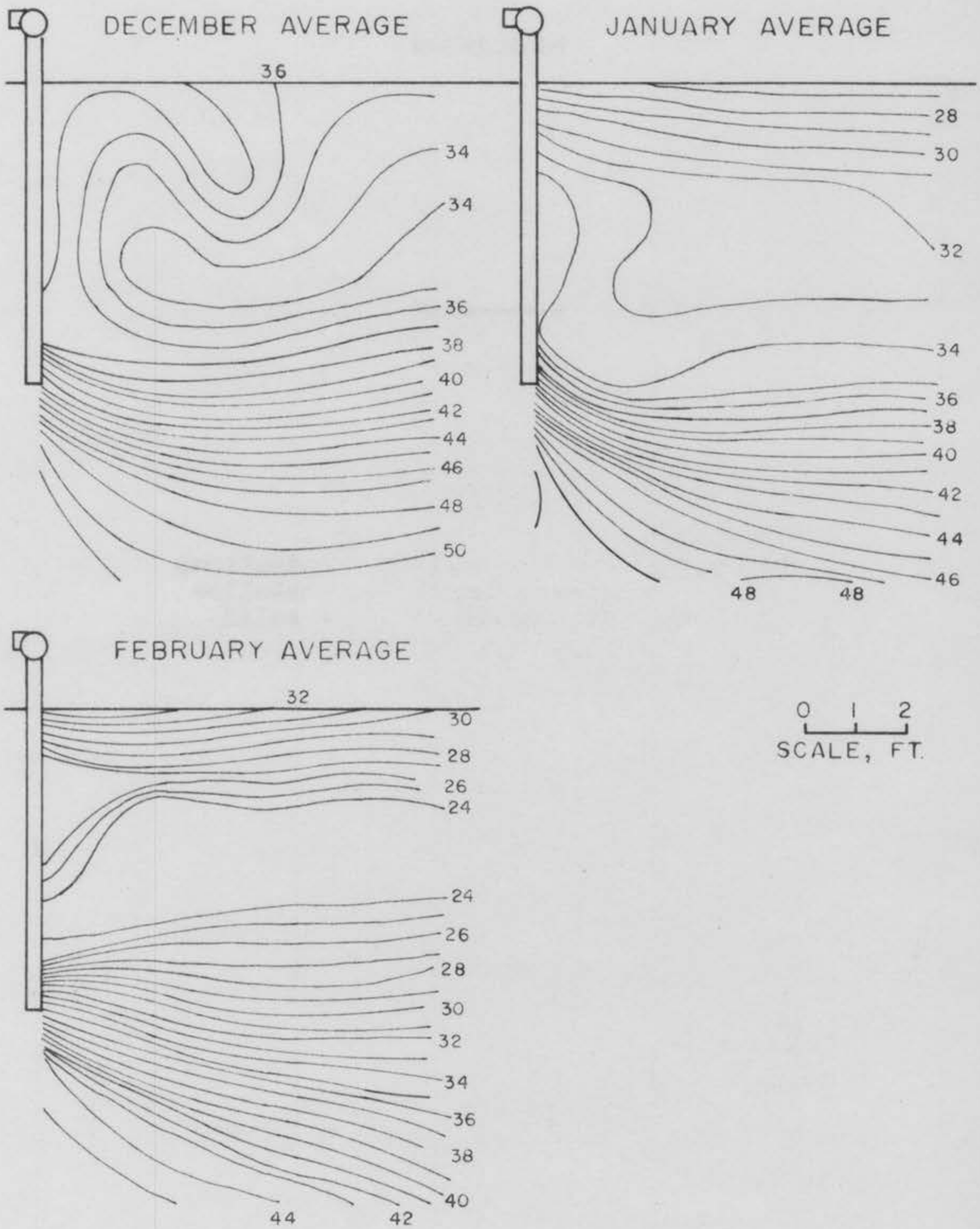
Figure 8. Average monthly temperatures around fan C, the installation having 6 ft of solid pipe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SCALE, FT.

Figure 9. Average monthly temperatures around fan B, the installation having 4 ft of solid and 1 ft of perforated pipe

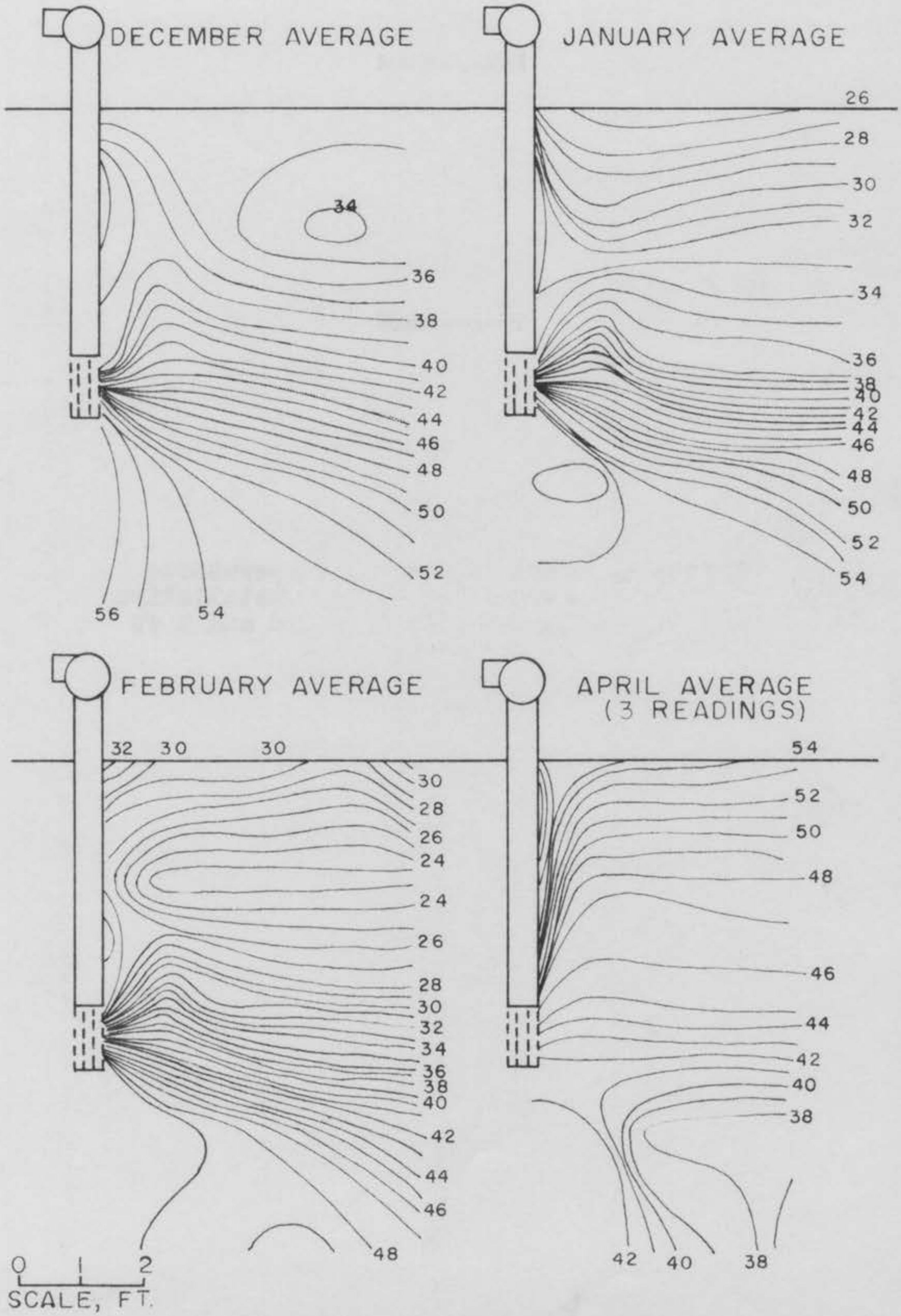

DECEMBER AVERAGE
34
36
38
40
42
44
46
48
50
52
56
54
JANUARY AVERAGE
26
28
30
32
34
36
38
40
42
44
46
48
50
52
54
FEBRUARY AVERAGE
32 30 30
30
28
26
24
24
26
28
30
32
34
36
38
40
42
44
46
48
APRIL AVERAGE
(3 READINGS)
54
52
50
48
46
44
42
40
38
42 40 38
0 1 2
SCALE, FT.

Figure 10. Average monthly temperatures around fan E, the installation having 6 ft of solid and 1 ft of perforated pipe

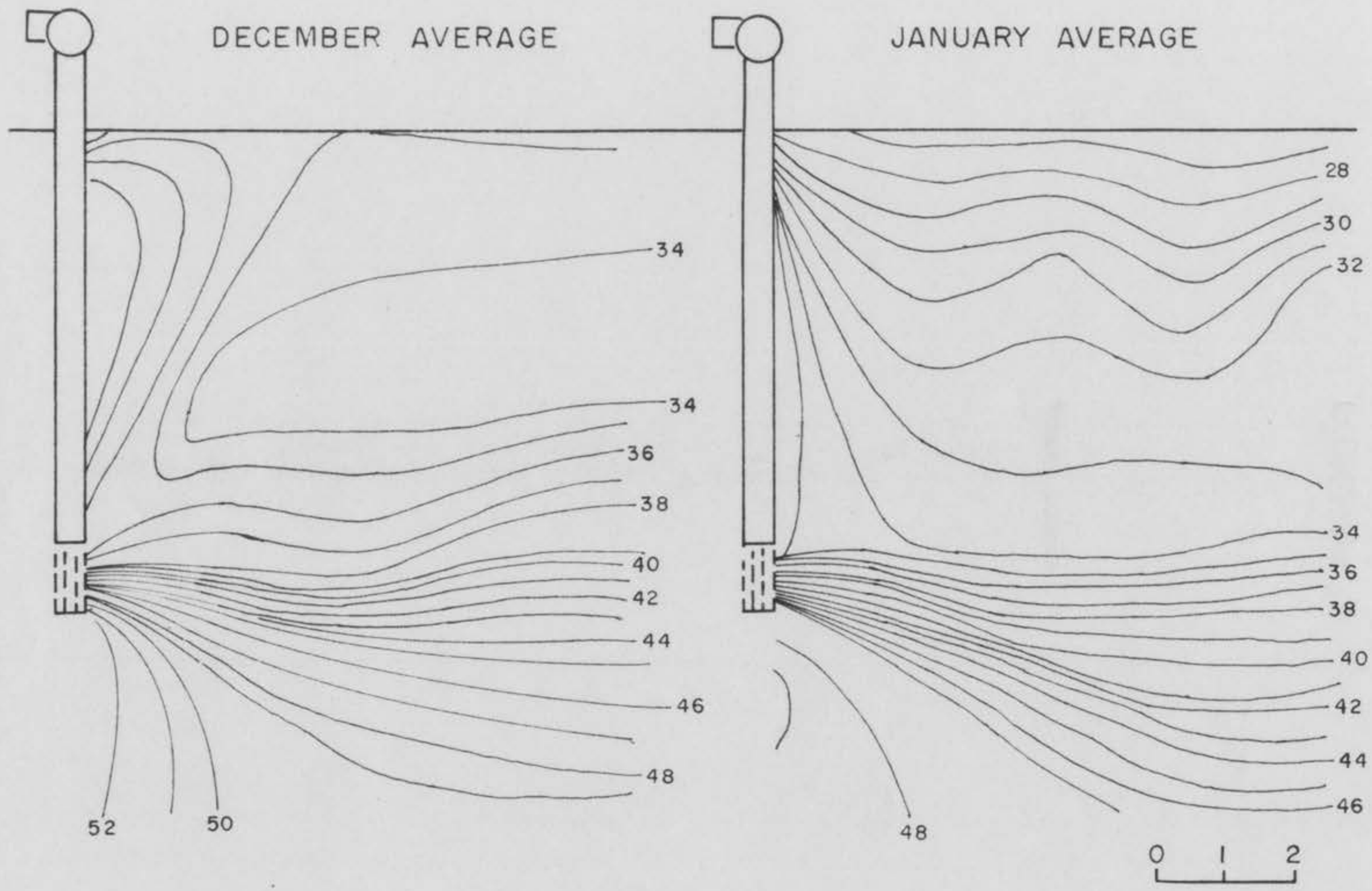

DECEMBER AVERAGE
34
34
36
38
40
42
44
46
48
52
50
JANUARY AVERAGE
28
30
32
34
36
38
40
42
44
46
48
0 1 2

Figure 11. Average monthly temperatures around fan E, the installation having 6 ft of solid and 1 ft of perforated pipe

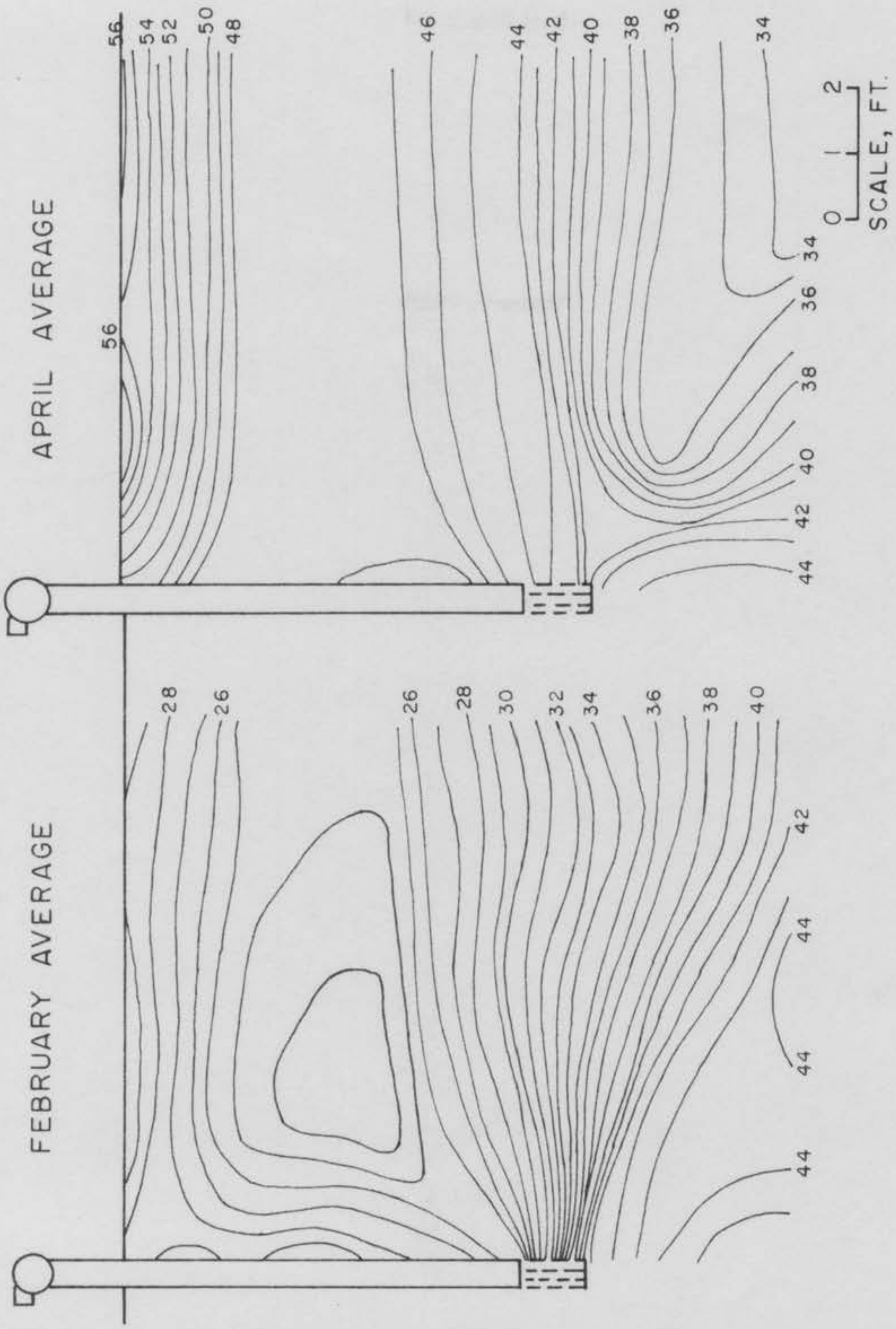

FEBRUARY AVERAGE
APRIL AVERAGE
56
54
52
50
48
46
44
42
40
38
36
34
28
26
26
28
30
32
34
36
38
40
42
44
44
44
0 1 2
SCALE, FT.

Figure 12. Average monthly temperatures around fan G, the installation having 8 ft of solid and 1 ft of perforated pipe

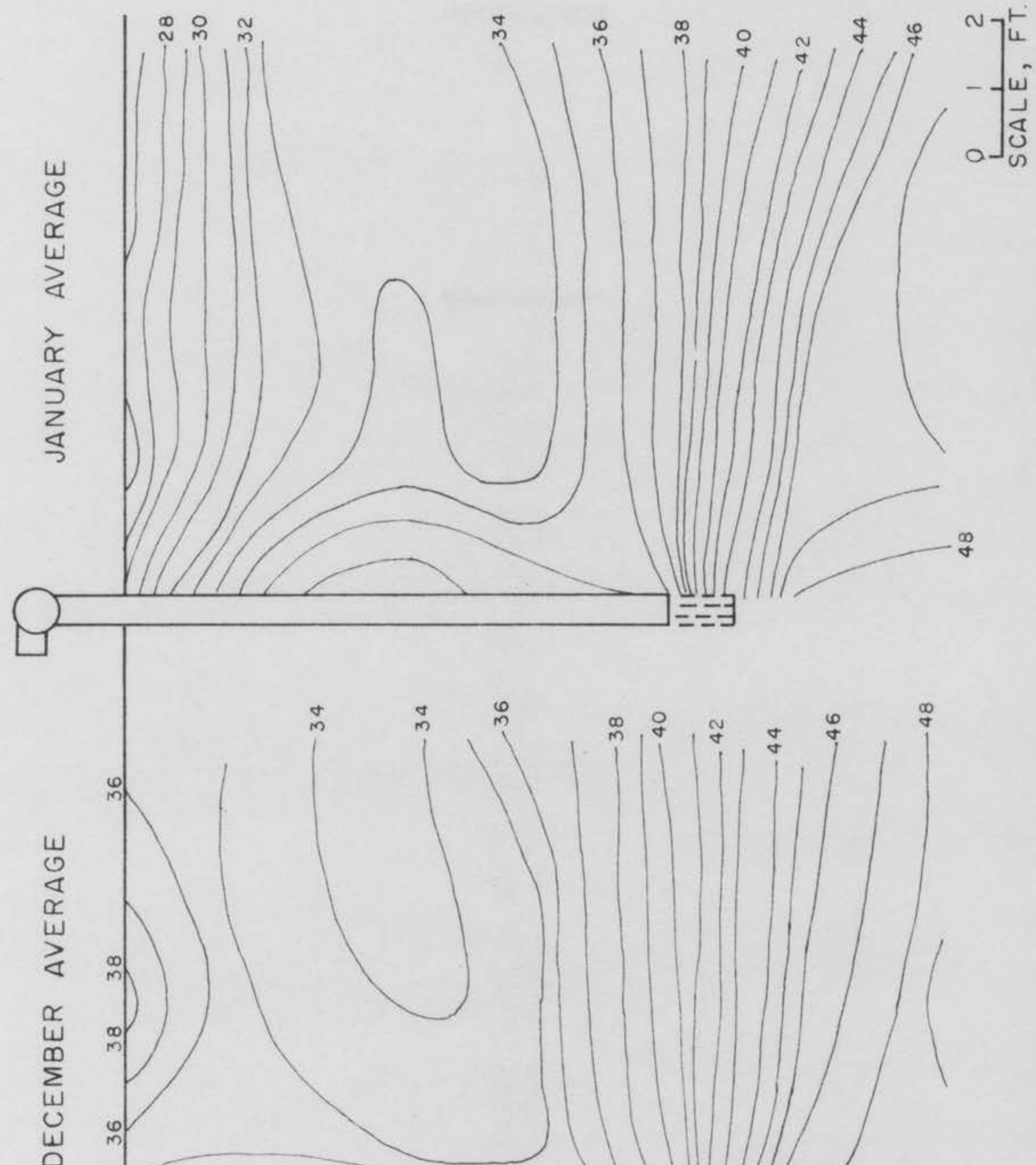

DECEMBER AVERAGE
36
36
38
38
36
34
34
36
38
40
42
44
46
48
50
JANUARY AVERAGE
28
30
32
34
36
38
40
42
44
46
48
0 1 2
SCALE, FT.

Figure 13. Average monthly temperatures around fan G, the installation having 8 ft of solid and 1 ft of perforated pipe

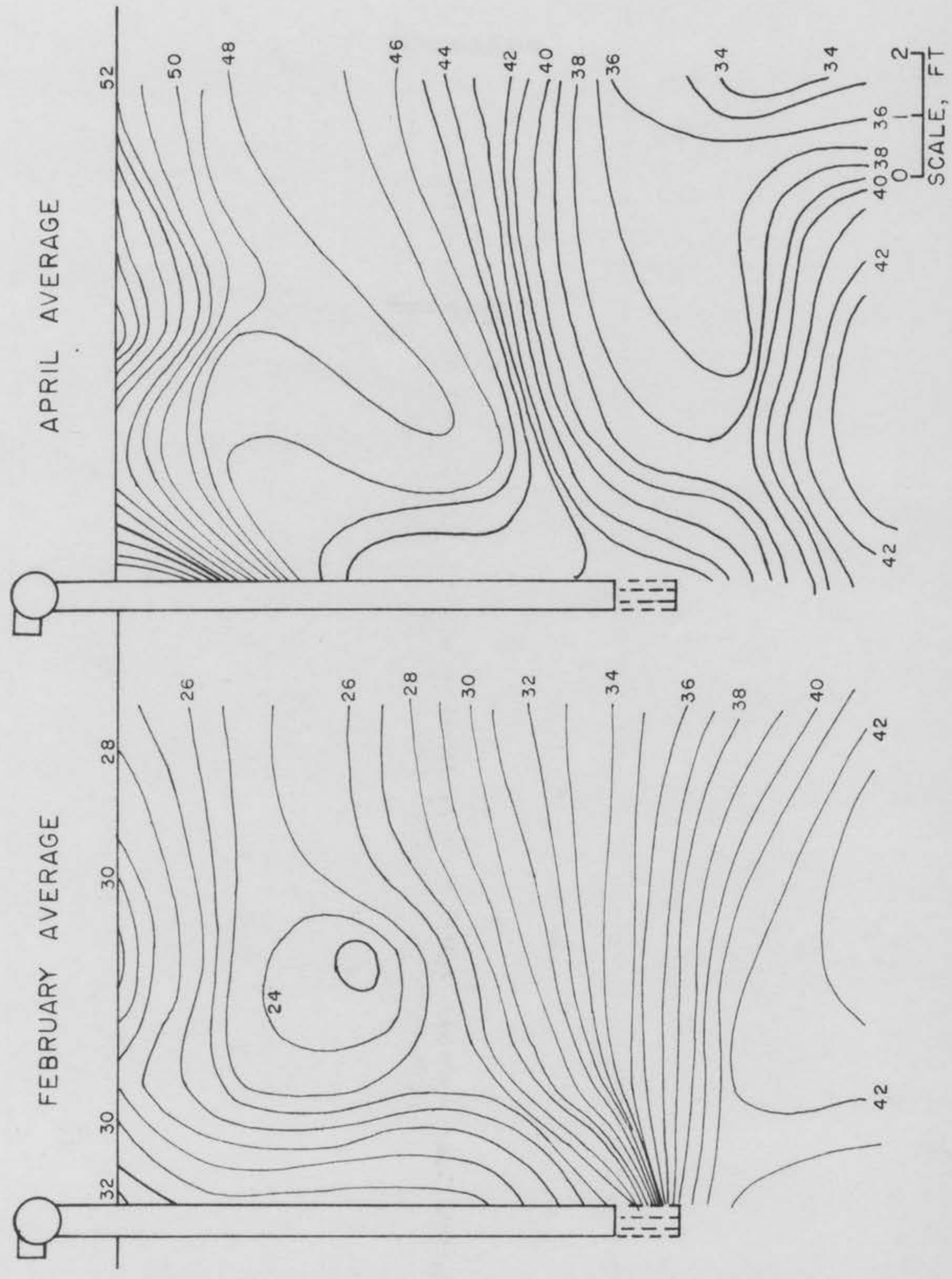

FEBRUARY AVERAGE
APRIL AVERAGE
SCALE, FT

Figure 14. Average monthly temperatures around fan D, the installation having 4 ft of solid and 3 ft of perforated pipe

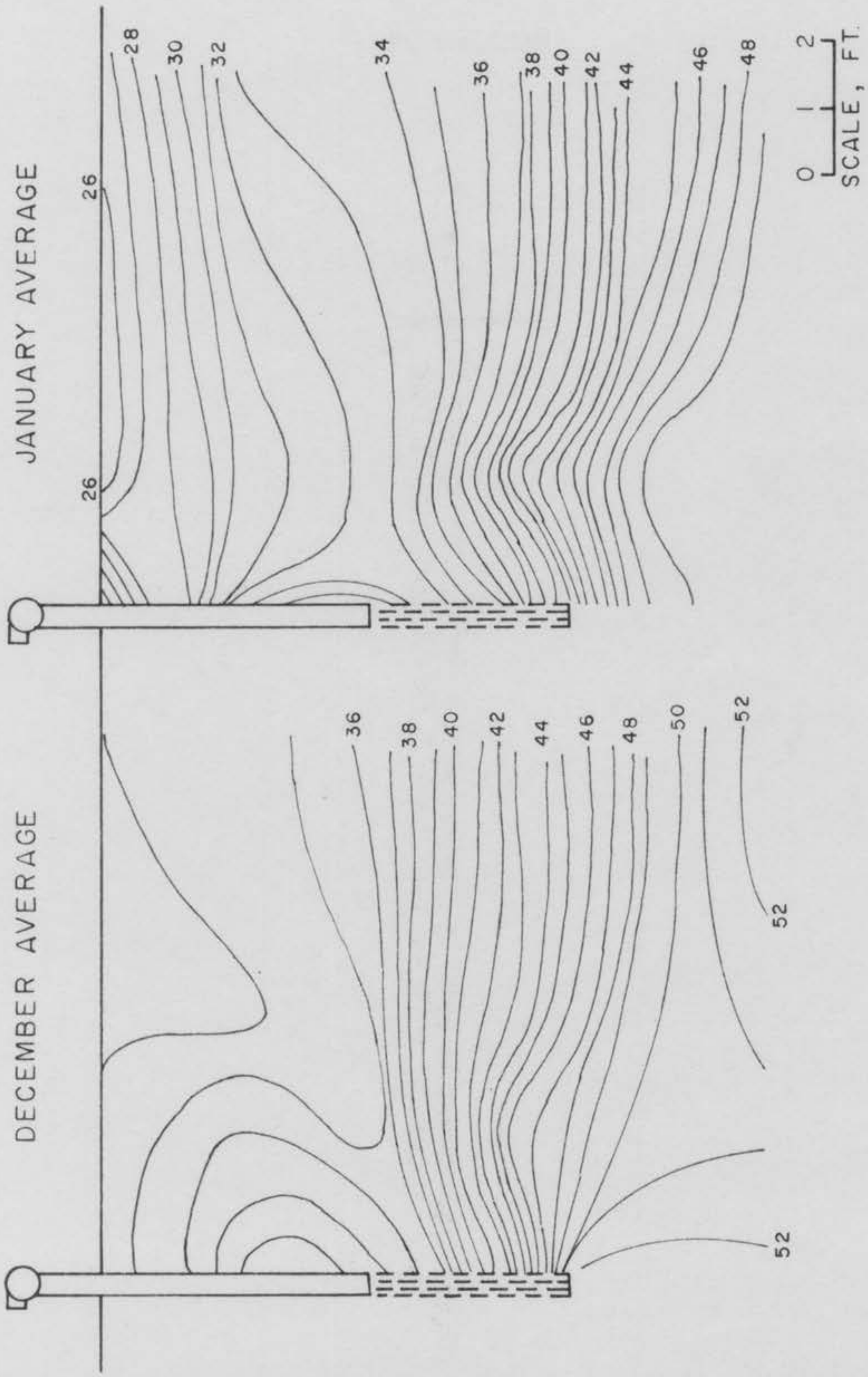

DECEMBER AVERAGE
JANUARY AVERAGE
26
26
28
30
32
34
36
38
40
42
44
46
48
36
38
40
42
44
46
48
50
52
52
52
0 1 2
SCALE, FT.

Figure 15. Average monthly temperatures around fan D, the installation having 4 ft of solid and 3 ft of perforated pipe

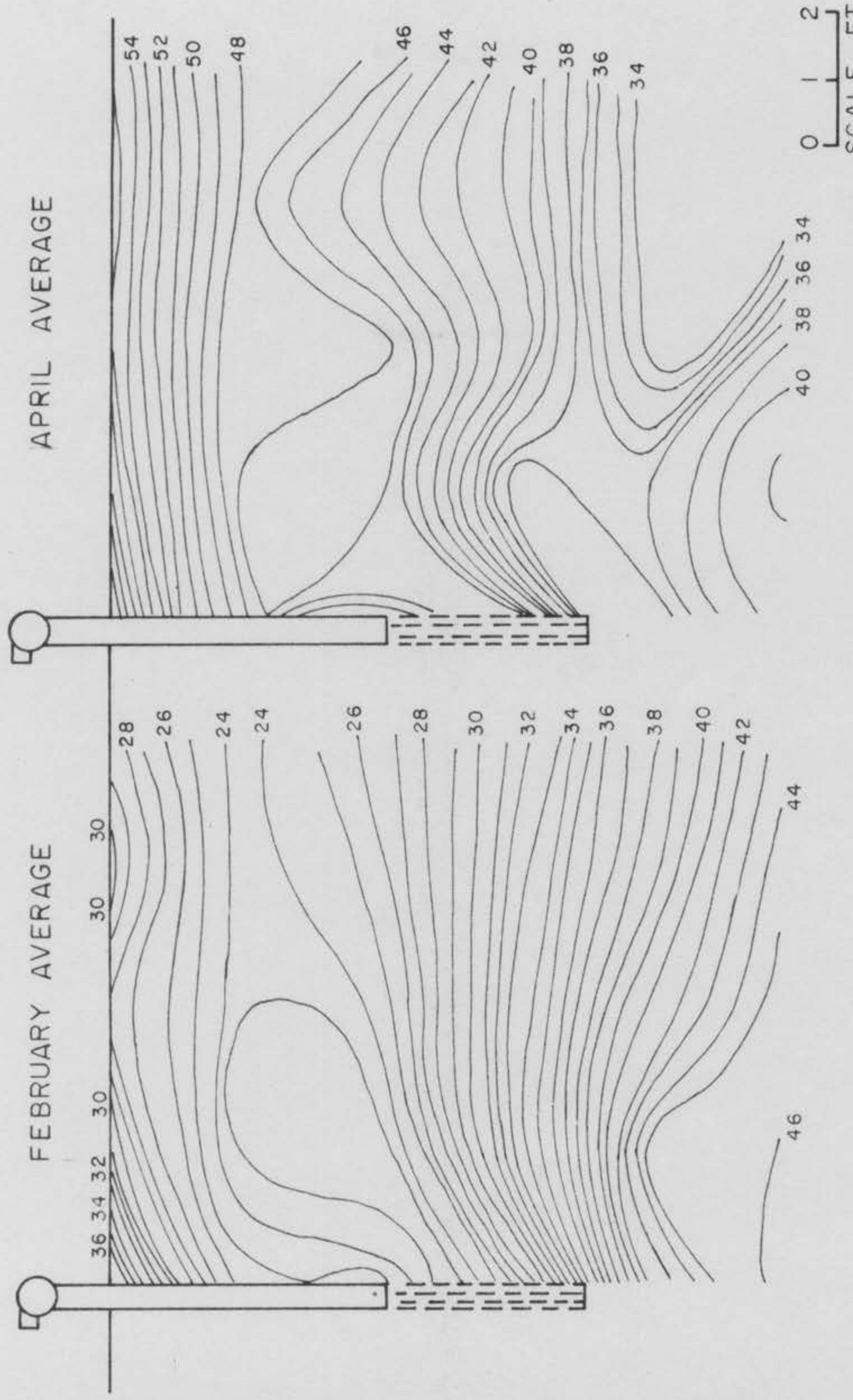
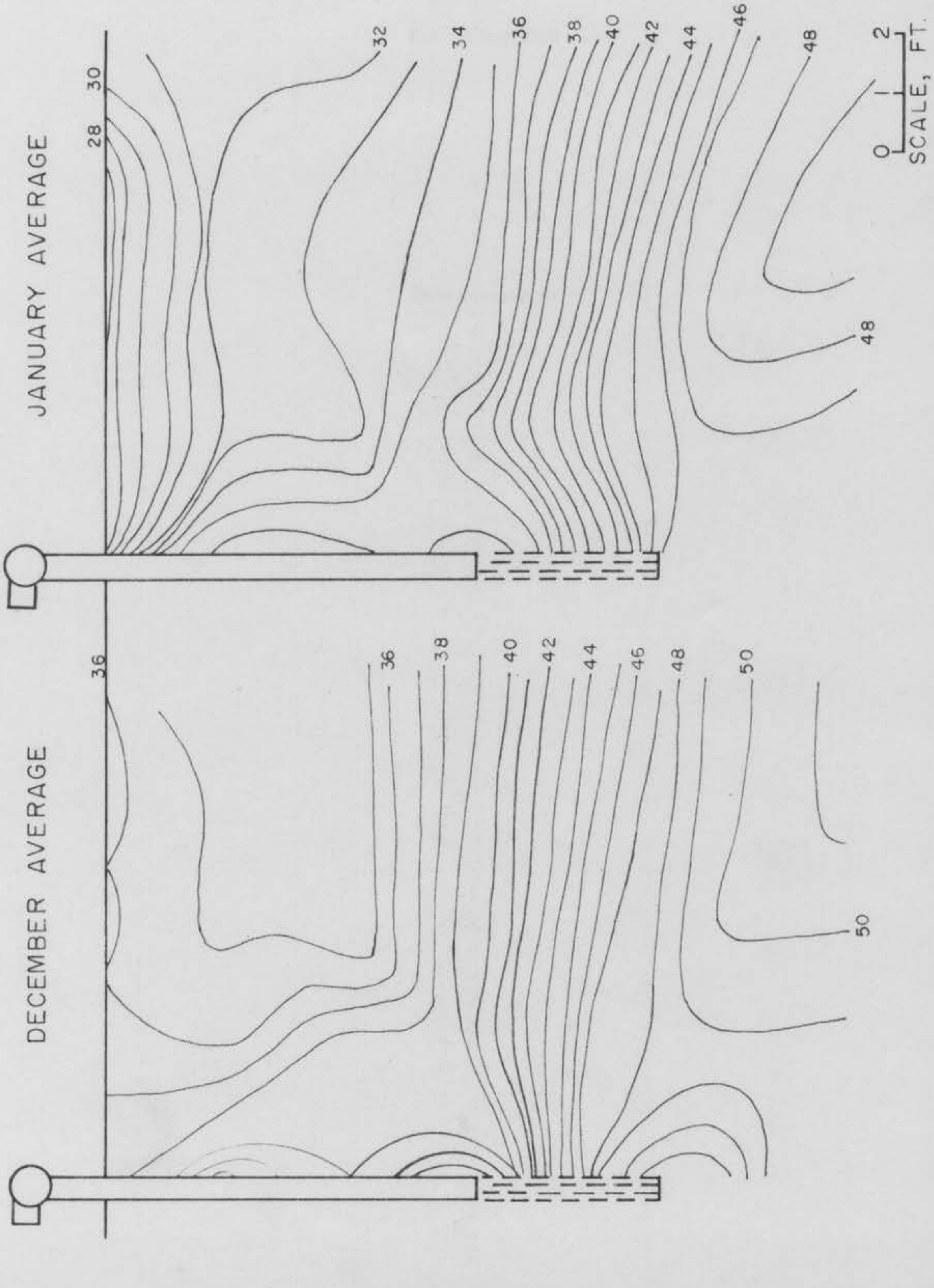

FEBRUARY AVERAGE
APRIL AVERAGE
0 1 2
SCALE, FT.
54 52 50 48 46 44 42 40 38 36 34
34 36 38 40
28 26 24 24 26 28 30 32 34 36 38 40 42 44
30 30 30
36 34 32 46

Figure 16. Average monthly temperatures around fan F, the installation having 6 ft of solid and 3 ft of perforated pipe



JANUARY AVERAGE
28
30
32
34
36
38
40
42
44
46
48
48
0 1 2
SCALE, FT.
DECEMBER AVERAGE
36
36
38
40
42
44
46
48
50
50

Figure 17. Average monthly temperatures around fan F, the installation having 6 ft of solid and 3 ft of perforated pipe

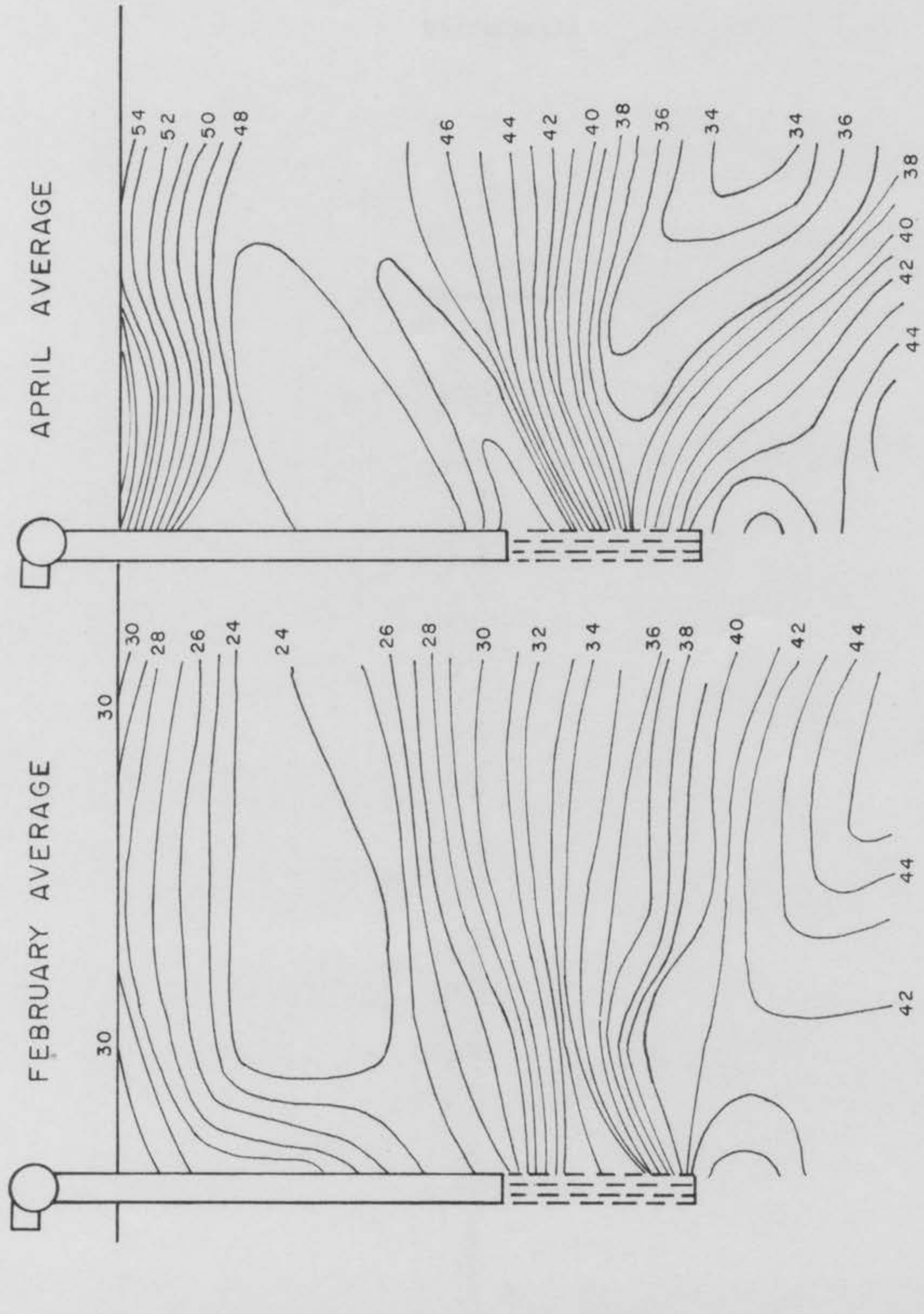

FEBRUARY AVERAGE
APRIL AVERAGE
30
30
30
28
26
24
24
26
28
30
32
34
36
38
40
42
44
44
42
54
52
50
48
46
44
42
40
38
36
34
34
36
38
40
42
44

Figure 18. Average monthly temperatures around fan H, the installation having 8 ft of solid and 3 ft of perforated pipe

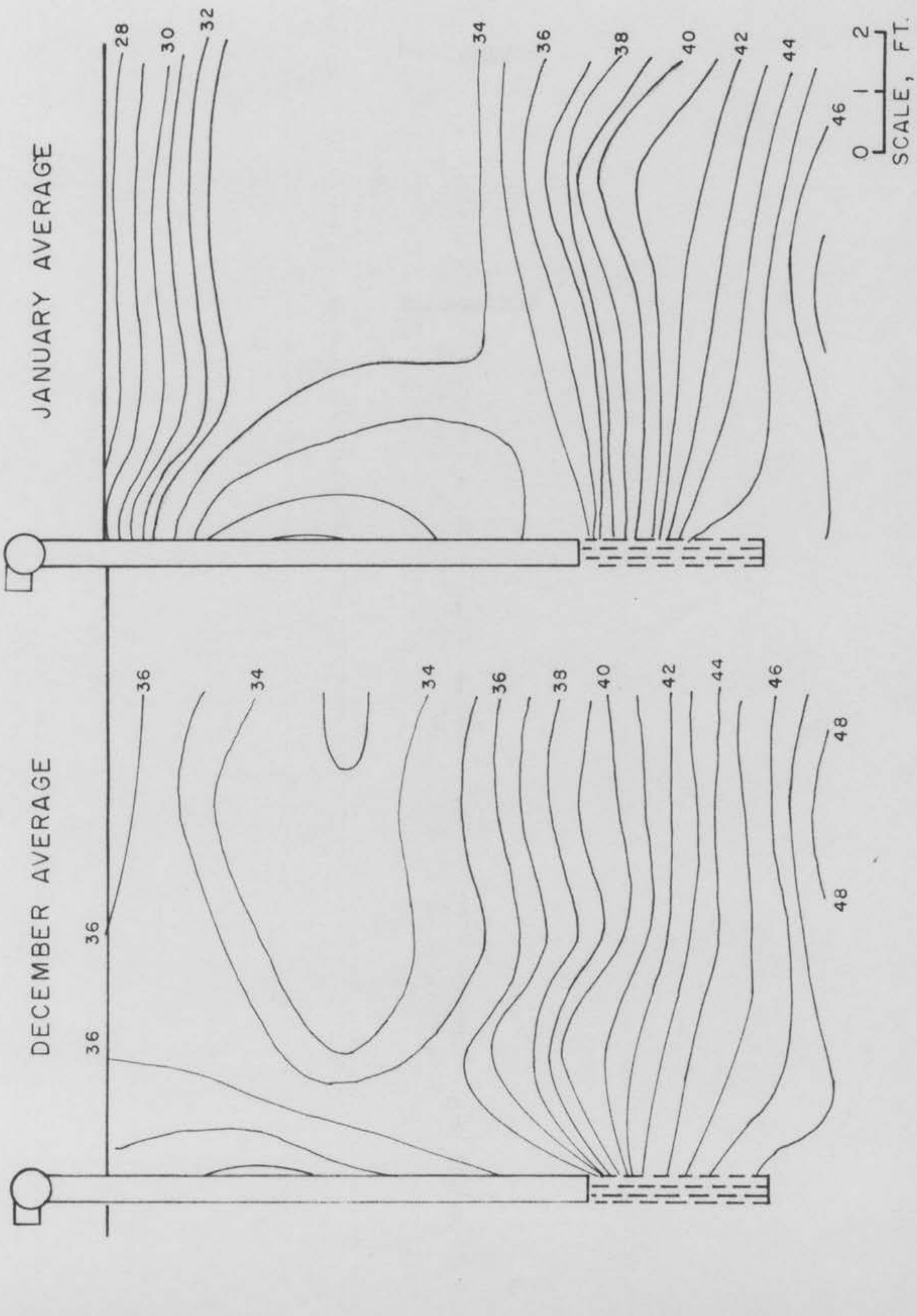

DECEMBER AVERAGE
JANUARY AVERAGE
28
30
32
34
36
38
40
42
44
46
48
0 1 2
SCALE, FT.

Figure 19. Average monthly temperatures around fan H, the installation having 8 ft of solid and 3 ft of perforated pipe

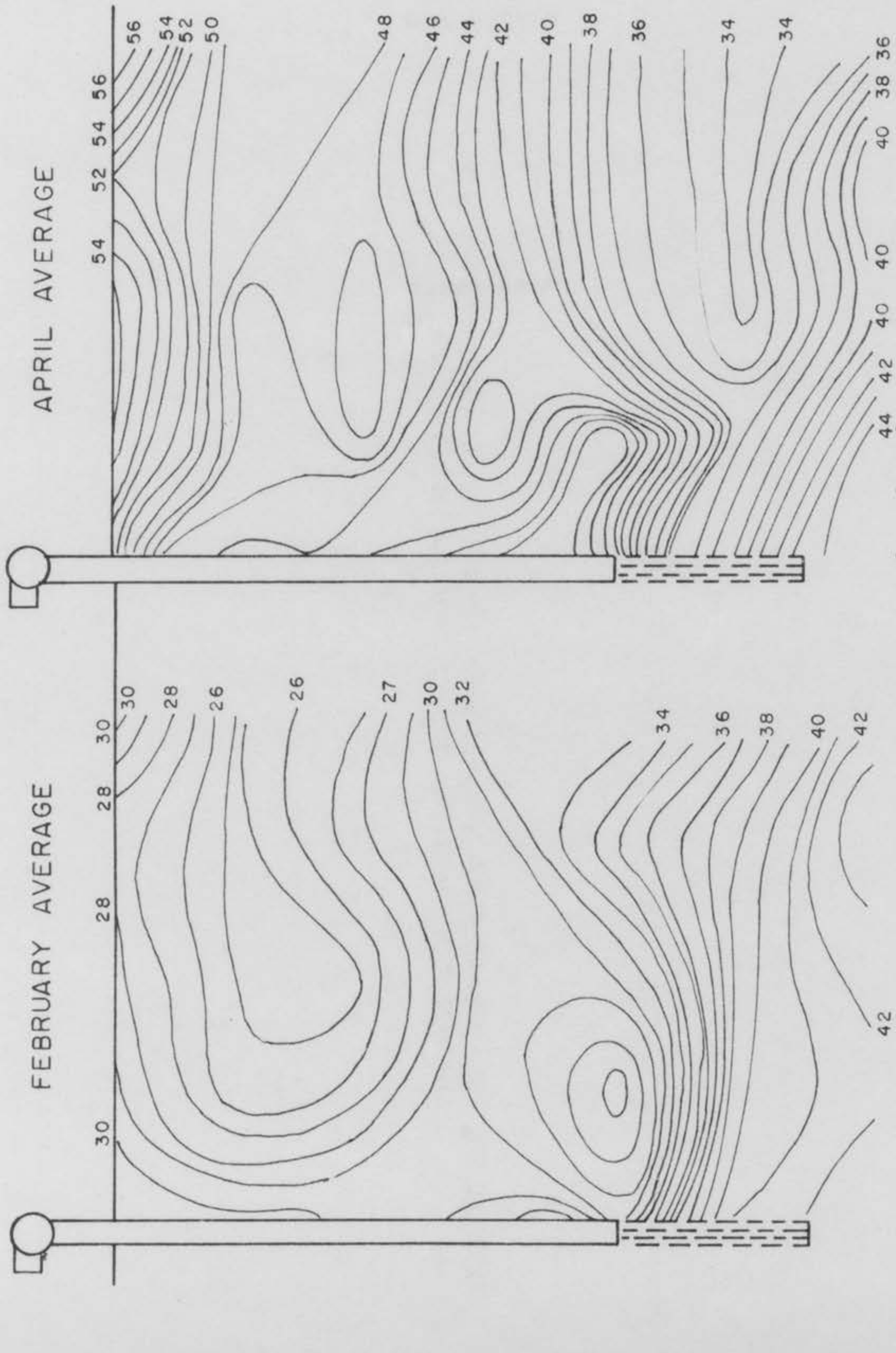
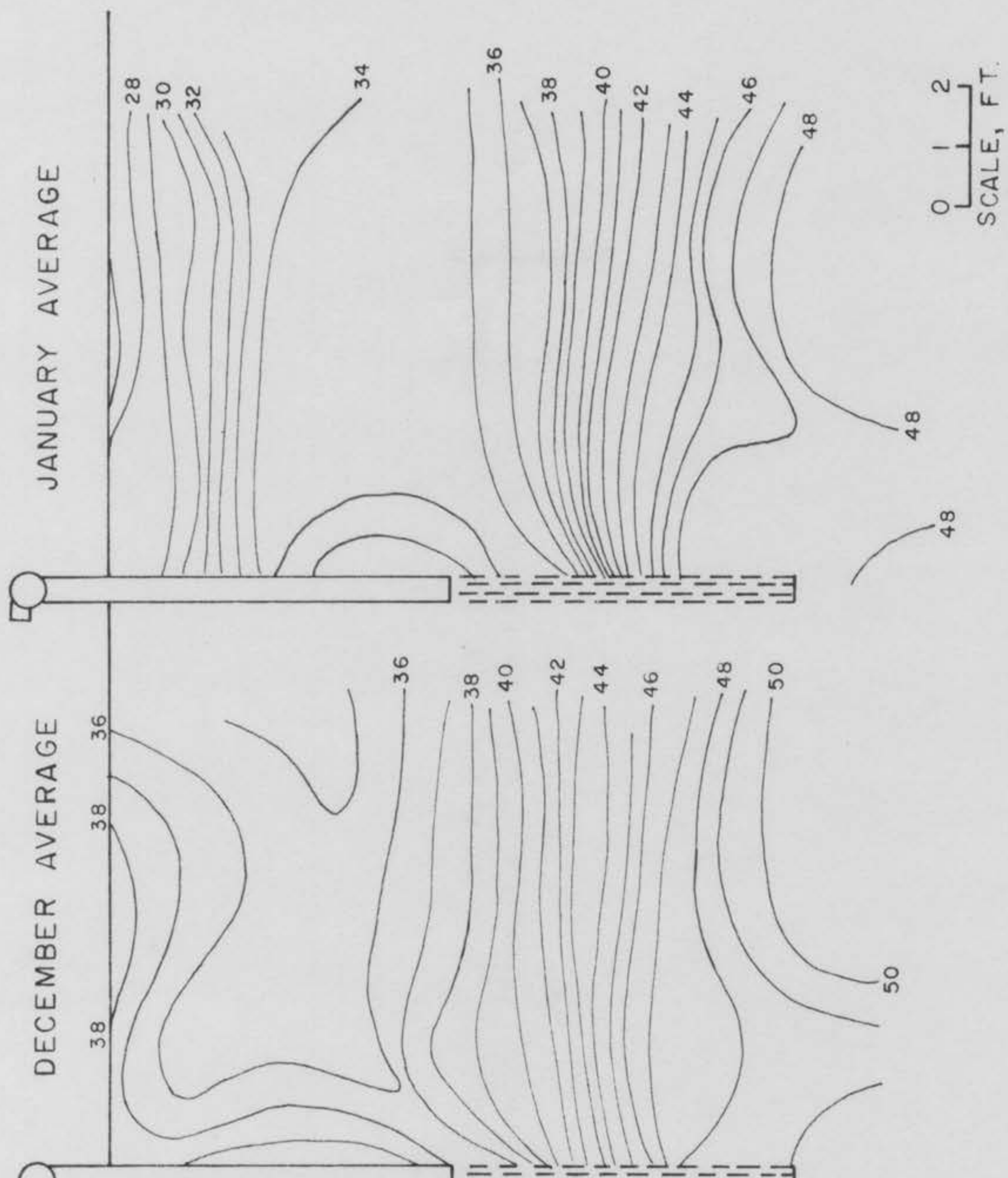

APRIL AVERAGE
FEBRUARY AVERAGE
SCALE, FT.
0
1
2
56
54
52
50
48
46
44
42
40
38
36
34
30
28
27
26
32

Figure 20. Average monthly temperatures around fan I, the installation having 6 ft of solid and 6 ft of perforated pipe



JANUARY AVERAGE
DECEMBER AVERAGE
28
30
32
34
36
38
40
42
44
46
48
50
SCALE, FT.
0 1 2

Figure 21. Average monthly temperatures around fan I, the installation having 6 ft of solid and 6 ft of perforated pipe

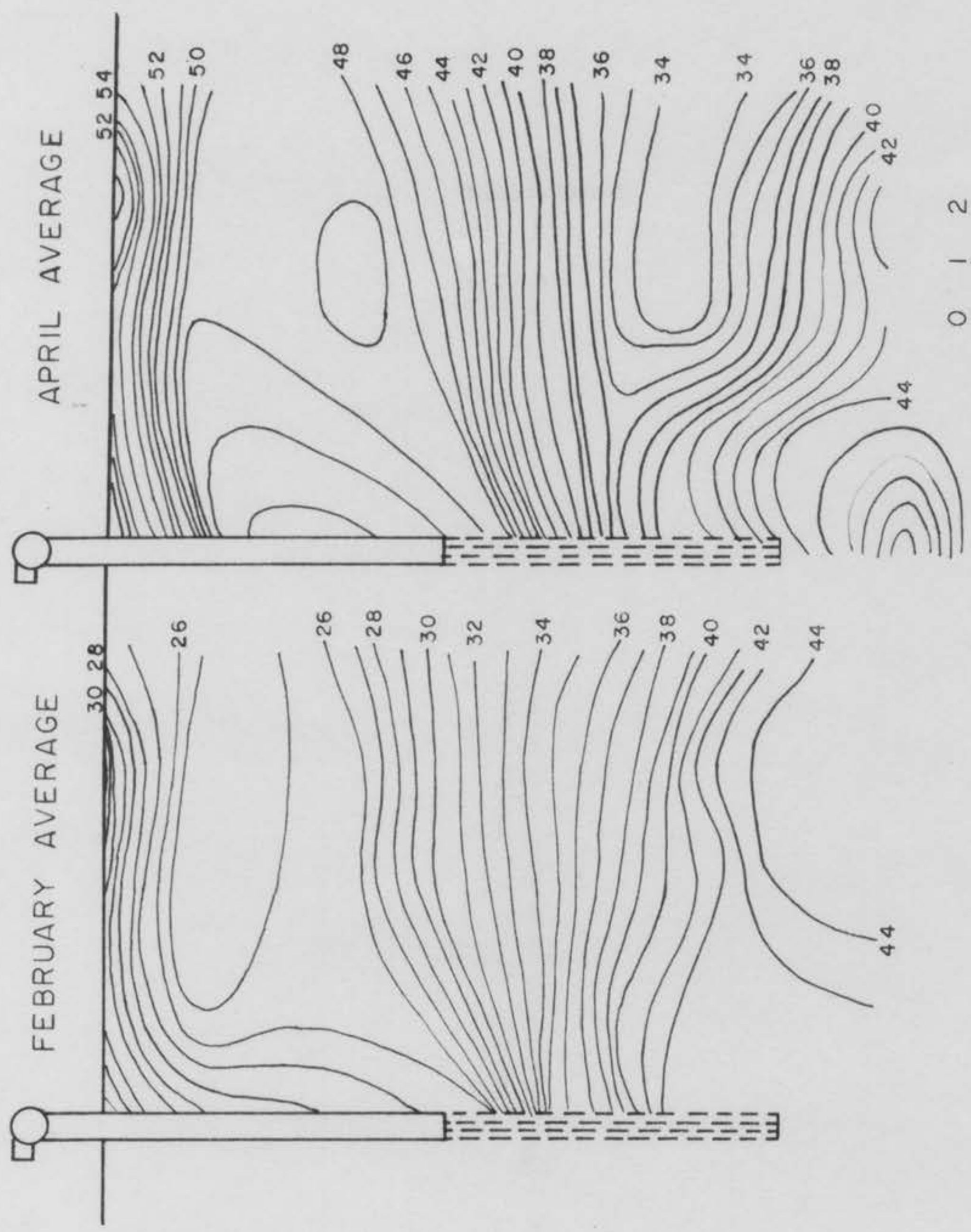
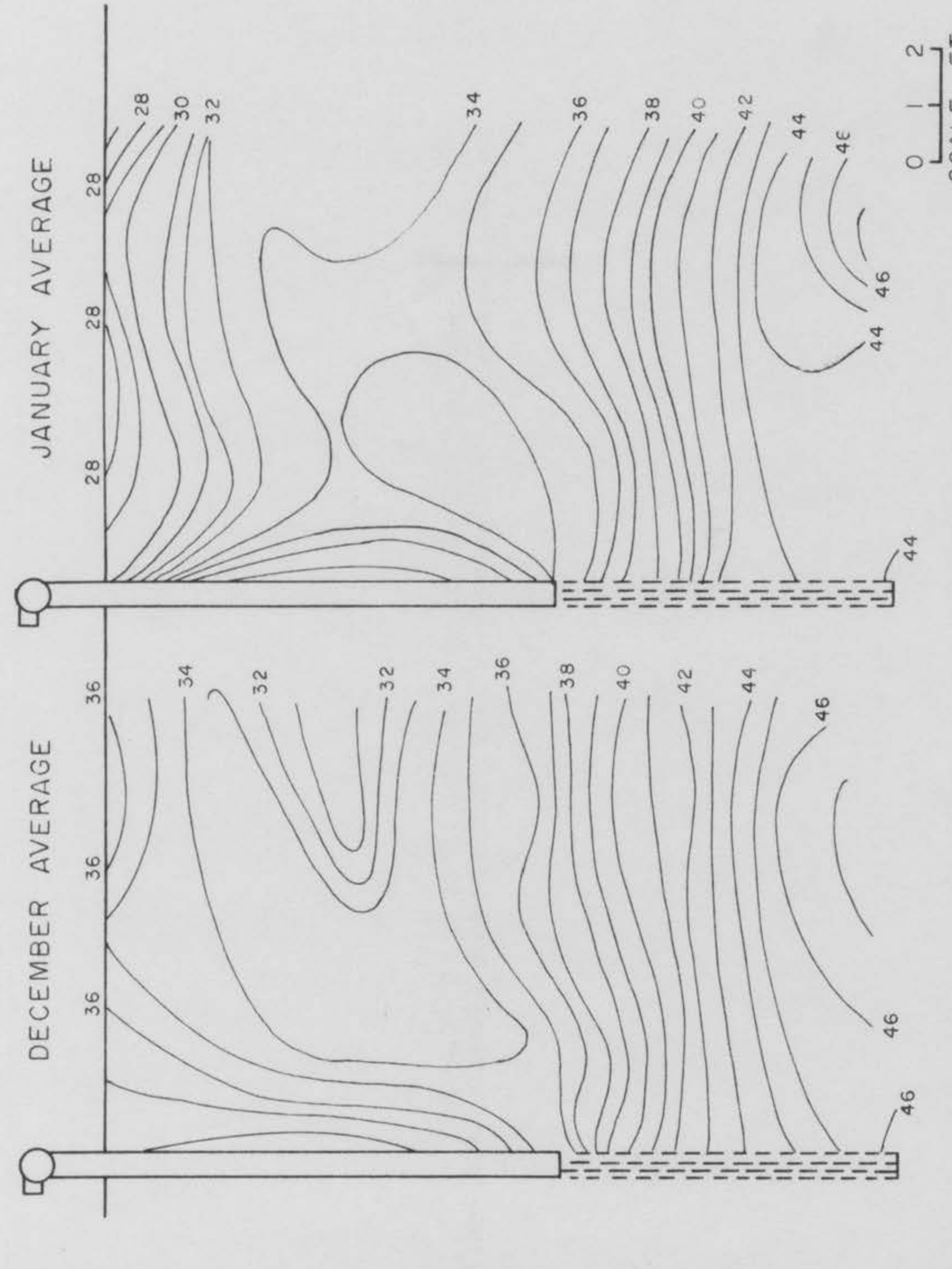
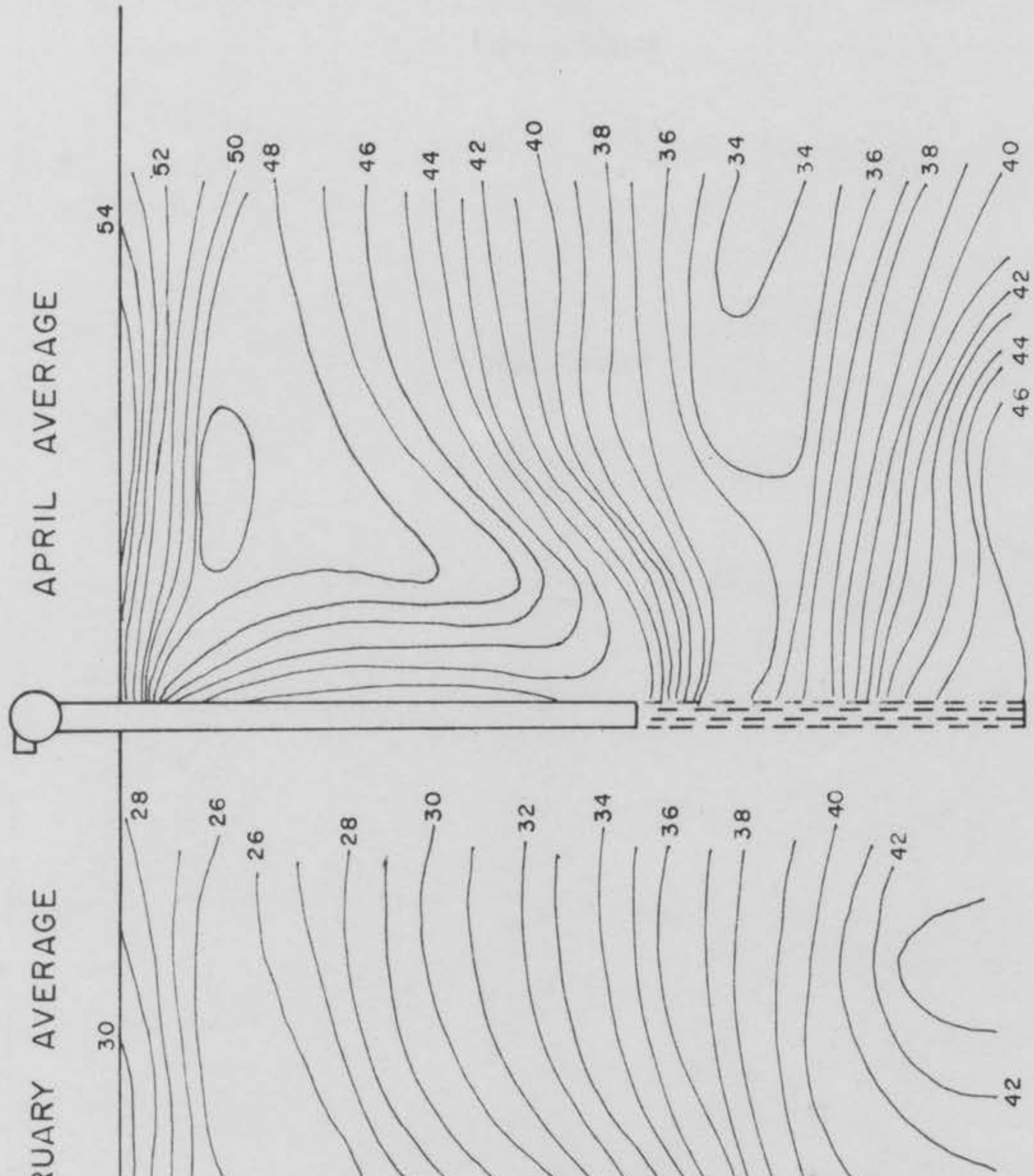

FEBRUARY AVERAGE
APRIL AVERAGE
30 28
26
26
28
30
32
34
36
38
40
42
44
44
52 54
52
50
48
46
44
42
40
38
36
34
34
36
38
40
42
44
0 1 2
SCALE, FT.

Figure 22. Average monthly temperatures around fan J, the installation having 8 ft of solid and 6 ft of perforated pipe



JANUARY AVERAGE
DECEMBER AVERAGE
28
30
32
34
36
38
40
42
44
46
0 1 2
SCALE, FT

Figure 23. Average monthly temperatures around fan J, the installation having 8 ft of solid and 6 ft of perforated pipe



FEBRUARY AVERAGE
APRIL AVERAGE
30
28
26
26
28
30
32
34
36
38
40
42
42
40
54
52
50
48
46
44
42
40
38
36
34
34
36
38
40
42
44
46
0 1 2
SCALE, FT.

Table 6. Moisture content of grain around fan systems

Fan system	Cable position number	Depth 0-6"	6-12"	1-2'	4'	Date
A	1	13.69	12.78	12.39	11.27	12-20-57
	2	14.00	12.87	12.39	11.75	12-20-57
	3	13.49	12.00	12.00	11.52	12-20-57
	4	13.69	12.20	12.39	11.75	12-20-57
	5	12.96	10.81	12.39	11.39	12-20-57
B	1	13.69	12.20	11.27	12.39	12-20-57
	2	14.12	12.67	11.13	12.53	12-20-57
	3	13.69	11.75	10.81	12.53	12-20-57
	4	14.23	13.23	11.13	12.67	12-20-57
	5	13.49	12.67	11.75	12.87	12-20-57
	6	12.87	12.78	12.39	12.78	12-20-57
C	1	13.19	12.85	12.40	12.17	12-27-57
	2	13.33	12.85	12.40	12.57	12-27-57
	3	13.19	13.05	12.17	12.85	12-27-57
	4	13.33	13.05	12.17	12.65	12-27-57
	5	13.33	12.85	12.04	12.40	12-27-57
	6	13.48	13.05	12.40	12.40	12-27-57
D	1	13.86	13.32	12.67	12.39	12-20-57
	2	13.86	13.49	13.67	12.53	12-20-57
	3	13.86	13.05	12.39	12.20	12-20-57
	4	13.86	13.14	12.53	12.00	12-20-57
	5	13.86	12.96	12.20	11.75	12-20-57
	6	13.69	12.53	12.20	11.84	12-20-57
E	1	13.71	12.42	12.61	12.29	1-9-58
	2	13.36	13.00	13.00	12.75	1-9-58
	3	13.91	13.45	13.00	12.61	1-9-58
	4	13.71	13.09	13.00	12.75	1-9-58
	5	13.71	13.27	13.00	12.61	1-9-58
	6	15.13	13.91	13.09	12.89	1-9-58
F	1	13.49	12.37	12.37	11.56	1-9-58
	2	14.03	13.40	12.70	11.92	1-9-58
	3	13.97	13.16	12.70	11.92	1-9-58
	4	13.80	12.98	12.50	12.31	1-9-58
	5	13.60	13.25	12.64	12.50	1-9-58
	6	14.45	13.46	12.89	12.64	1-9-58

Table 6. (Continued)

Fan system	Cable position number	Depth				Date
		0-6"	6-12"	1-2'	4'	
G	1	12.94	12.27	12.11	11.79	1-9-58
	2	13.22	12.80	12.47	11.79	1-9-58
	3	13.31	12.70	12.37	11.69	1-9-58
	4	13.40	12.70	12.37	11.81	1-9-58
	5	13.40	12.84	12.70	11.92	1-9-58
	6	14.03	13.40	13.04	11.92	1-9-58
H	1	12.56	11.92	11.44	11.15	1-9-58
	2	13.22	12.37	12.37	11.30	1-9-58
	3	13.23	12.80	12.66	11.54	1-9-58
	4	13.40	12.70	12.37	11.81	1-9-58
	5	13.23	13.14	12.94	11.91	1-9-58
	6	13.96	13.59	12.94	11.91	1-9-58
I	1	12.80	11.66	11.54	11.08	1-9-58
	2	13.32	12.80	12.27	11.08	1-9-58
	3	13.32	12.66	12.02	11.08	1-9-58
	4	13.14	12.02	11.91	11.40	1-9-58
	5	12.94	12.27	12.02	11.40	1-9-58
	6	13.96	12.80	12.66	11.54	1-9-58
J	1	13.00	12.61	12.29	11.97	1-9-58
	2	13.36	12.89	12.89	11.97	1-9-58
	3	13.27	12.75	12.75	11.86	1-9-58
	4	13.36	12.61	12.89	11.61	1-9-58
	5	13.45	12.89	12.89	11.74	1-9-58
	6	14.76	13.54	13.09	11.86	1-9-58

Figures 7 and 8 present the average temperatures around ducts which had no perforated pipe, whatever. The results from these two are not significant in themselves since it is recognized that this arrangement would have doubtful value in a practical situation. There are certain things which appear here that also appear in other diagrams; therefore, it seems advantageous to cover them at this time.

The change in temperature of the grain is dependent on the passage of air which has a temperature different from that of the grain. If it could be assumed that a mass of grain had a constant initial temperature throughout, and air with a different constant temperature was moved through the grain, there would be a temperature gradient between the portion of the grain which was still at the initial temperature and that which had reached the temperature of the air stream. This temperature gradient can be represented by isotherms drawn through a cross-section of the grain. If the amount of air which was flowing through the grain varied at different positions, then the isotherms would not be straight lines as they would before, but would vary in distance from their starting position according to the rate of air flow at that position. This, essentially, is the problem dealt with here. Since these fans are theoretically drawing air from every point in the bin, then the rate of flow will be different at different points. Thus, one would expect the isotherms to have shapes which would vary, somewhat, according to the amount and direction of air flow.

The results in Figures 7 through 23 are in terms of isotherms around the fan systems. It would be helpful to analyze one of these isotherms. Take the one representing 40° F in the December average in Figure 7. It is almost parallel to the grain surface until it gets very close to the vertical duct. At a distance of approximately 12 in. from the duct, it dips downward. This means that the nearer one approaches the duct, the further a point representing 40^{o} has progressed, which means that the amount of air moving per unit area is increasing as one approaches the duct. Very near the duct, in all cases, the isotherms turn upward and show that there is a temperature gradient outward from the duct. It is believed that this is due to warmer air from deeper in the bin. This warmer air moving through the duct warms the duct which, in turn, warms the surrounding grain, producing this temperature gradient. It is believed that if there was thermal insulation around the duct, this phenomenon would disappear.

It should be noted that there are isotherms below the duct which slope upward toward the duct opening. From the analysis above, this would mean that there is air moving upward in the bin and into the duct. Since these drawings represent a period of time when the natural movement of air in the bin would be upward at this point, this would mean that these fans are drawing off the air which is supplied by the convection currents.

The relative distances between lines of constant temperature should be taken into consideration, also. The distances between these lines actually represent the temperature gradient in any direction. The purpose of vertical-duct ventilators is to eliminate temperature gradients between various regions of bins of grain; therefore, it is desirable that this be minimized, as much as possible.

In Figures 7 and 8, in all cases, there is a region near the inlet of the duct where the temperature gradient in the vertical direction is relatively large. This means that the point of entrance into the duct is so small that all the air moving into it must pass through a relatively small region, thus crowding these lines very close together.

Attention is called to the February average in Figures 7 and 8. Here, the lines of constant temperature above the entrance into the duct have virtually ceased to dip down which would indicate that there is little air being drawn downward. This is the time that the convection currents are at their maximum; thus, the shape of these lines would indicate that the major portion of the air that is being exhausted through these systems comes from below.

In Figures 9-13 are represented the monthly averages for the systems having 1 ft of perforated pipe. Here, as before, there is found a region above the junction between the perforated and solid pipes where the temperature gradient is small relative to the region adjacent to the perforated section. It should be noticed that the diagrams for the February averages show this region to have more lines running through it which means, as before, that the fans are receiving most of their air from the convection currents and draw very little directly from the surface of the grain. In the April average, the pattern is disrupted which means that a change is taking place. This change would mean that April is when the convection currents are having little effect and the pattern of air flow is now becoming one which is directly from the surface toward the perforated section.

Figures 14-19 present the results of the systems having 3 ft of perforated pipe. Here, again, the region above the bottom of the solid pipe has a temperature gradient which is small compared to the perforated section. In the February averages, however, this is not as noticeable, again indicating that the air moving due to convection is of a volume such that very little is drawn from the surface directly to the duct. In all three cases, the April average is a pattern which is disrupted from that found previously, indicating, as before, that convection has virtually ceased.

As indicated by the concentration of lines of equal temperature around the perforated ducts, the 3-ft section does not give as sharp a temperature gradient, which is a desirable characteristic.

The Figures 20-23 give results for the systems having 6 ft of perforated pipe. The results from these are similar to the others except the distribution around the perforated pipe might be a bit more gradual.

The region which is affected seems to be influenced most by the length of the solid pipe more than that of the perforated pipe. In general, all the drawings show that the region above the junction of the two types of duct is the region affected, as long as the convection currents do not control the pattern. This means that a bin can be aerated with a relatively small fan as long as the fan has a capacity equal to, or larger than, the quantity of air flowing due to convection.

It will be noted in Figure 6 that the horizontal duct is relatively close to the end of the vertical duct. It might appear that this would have some effect on the aeration pattern. If this were to be an influence, it would have affected the rate of air flow from systems I and J. Results below indicate that such was not the case; therefore, the shape of the lines, in all cases, can be considered to be influenced by aeration and would have the same general shape if the horizontal duct were removed.

The results of the grain moisture contents cannot be evaluated except to note that, in all cases, the samples from the top six inches have the highest moisture content. Since these moisture contents are not a great deal larger than those at the 4-ft level, it is difficult to evaluate them in terms of the effectiveness of the aeration.

Investigation of the Effectiveness of Vertical Ducts with Continuous Warm-Weather Operation

Method of procedure

The method of procedure used here was identical in many respects to the investigation that was carried out with continuous cold-weather operation. For this reason, only the differences in procedure will be noted. Two bins were used which were identical to the one used previously but no fans had been operated in them so that the grain was still cold from the aeration it had received from the owner's fans during the winter. All systems were placed 8 ft from the center of the bin to place them further from the horizontal duct shown in Figure 6.

The systems with no perforated pipe were omitted but one was added which utilized 4 ft of solid and 6 ft of perforated pipe. The systems were placed at intervals of 16 ft. All thermocouple cables had 12-in. spacings between junctions. The cables were spaced such that the first one was next to the duct, the next two were at intervals of 12 in., the next two at intervals of 18 in., and the last one at 24 in., making a total of six cables used in all.

Readings were taken prior to starting the fan and then taken once a day, thereafter, for a week. Half of the fans were operated at one time, these tests occurring during June and July, 1958.

Results

The results of the study in continuous warm-weather operation are not shown with the exception of readings around fan I, which had 6 ft of perforated and 6 ft of solid pipe. The last five daily readings were averaged together, as before, and the chart drawn of the equal-temperature lines, as shown in Figure 24. By comparison with the April average for fan I, shown in Figure 21, it can be seen that there is not a great deal of difference between the shapes of the lines of constant temperature; however, since this fan had not been operated continuously throughout the past winter, but had only recently been inserted, it was felt that the results here should not be compared to the April averages in the other section.

A set of temperatures was taken at fan I, on the cable adjacent to the duct, prior to starting the fan in operation. These are shown in graphical form in Figure 25 with the corresponding parts of the duct. Also shown is the plot of the average temperatures at the same points along the duct a week after the fan had been in operation. The dotted curve will be discussed below.

Discussion of results

The solid lines in Figure 25 represent the actual measured temperatures before and after aeration. The lower portions of these two curves are essentially parallel. This would indicate that the aeration process has had very little effect at this depth and the difference between the two curves would represent nothing more than the warming of the grain due to natural causes. The dotted-line curve labelled "End temperatures without aeration" is a hypothetical curve representing what might have been the expected temperature curve at the time aeration was ended if aeration had never been introduced. The point at which this hypothetical curve and the real curve after aeration meet may have some significance, however. If this dotted-line curve is a true representation of what the temperature would have been, then the point at which these two curves meet would represent the point beyond which there was not enough air moving to produce any measurable change of grain temperature. This point, then, reading from Figure 25, would be at a point approximately 30 in. below the junction between the solid and perforated portions of the system. The 30 in. could then be thought of as the maximum length of perforated pipe needed to produce any measurable change in grain temperature.

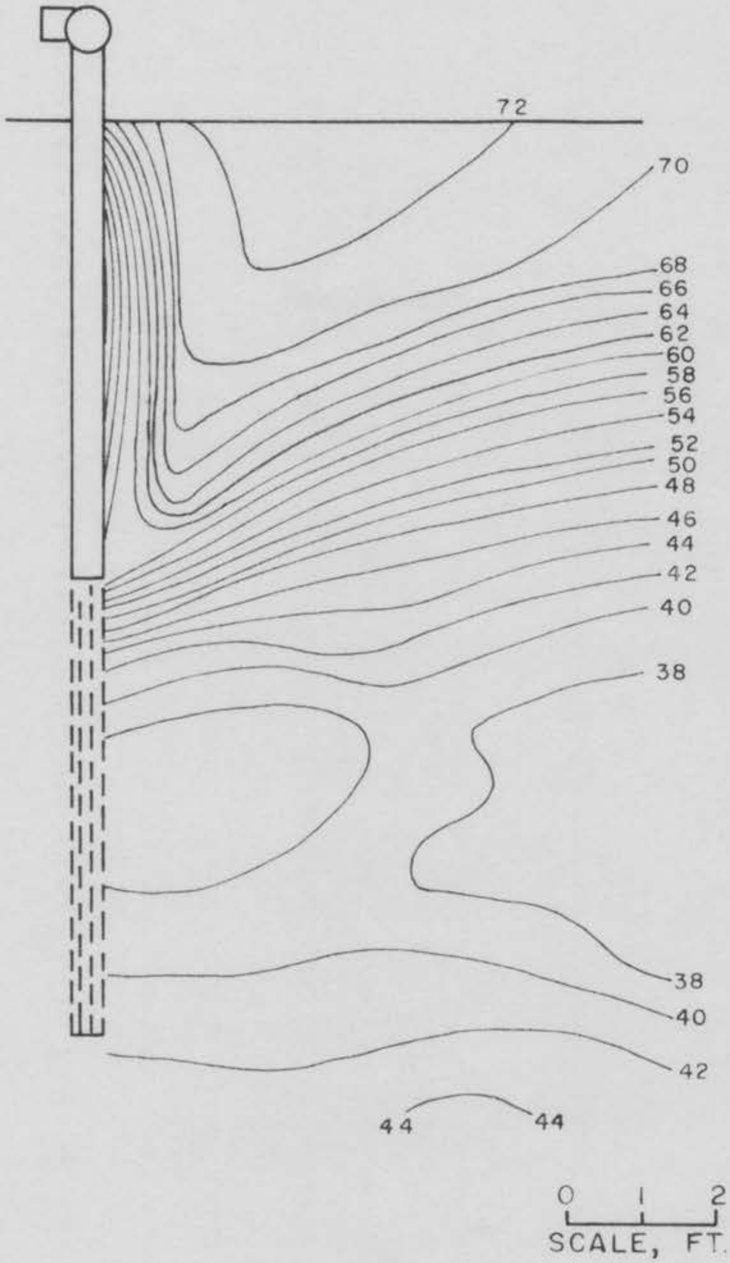


Figure 24. Average of five temperature readings around fan I, taken daily, June 8-13, 1958

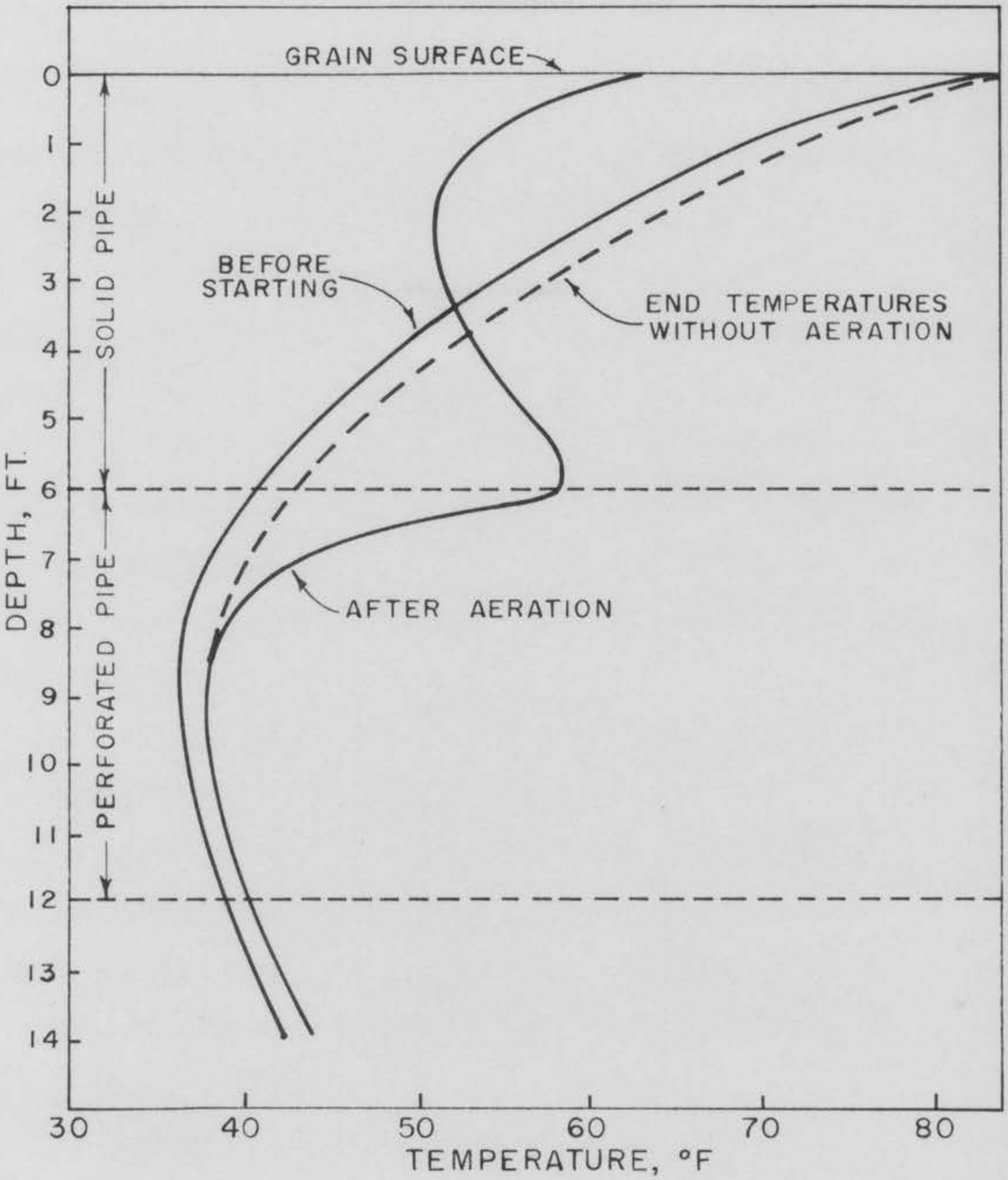


Figure 25. Temperatures along duct of fan I before and after aeration with the temperature which would have been expected at finish of test if no aeration had been used

Investigation of the Effect of Varying Amounts of Duct Work on the Amount of Air Flow

As shown in the section entitled Analysis of the Problem, it is possible to vary the amount of the perforated portion of the aeration systems, thereby varying the amount of air flow with any given fan. This portion of the manuscript is designed to present a study of what actually happens when the perforated duct is varied in length, with a given fan.

Method of procedure

Nine different systems were used, these being the ones that had been installed for the study in continuous warm-weather operation. One fan was used for all the readings, it being similar to those used for the other portions of this manuscript.

The air flow was measured by measuring the differential pressure across the fan. The fan was calibrated by use of calibrated, perforated, metal sheet as used by Shedd (7), where measurement of the differential pressure across the metal sheet is a measure of the air flowing.

The apparatus is shown dissembled in Figure 26, which also shows the perforations. The barrel-like portion, which has the perforated sheet metal on one end, acts as a plenum chamber while the conical-shaped pipe attached to the fan serves to permit the air from the fan to be exhausted far enough from the perforations to minimize the effects of velocity pressure. The fan is fastened to the plenum with four bolts with the conical pipe within the plenum. There is a rubber gasket between the fan and plenum and all joints on the plenum are taped such that air can escape only by passing through the perforations. The differential pressure is measured by means of a pressure tap in the side of the plenum. The instrument used to measure the pressure was a Magnehelic Gage, manufactured by F. W. Dwyer Manufacturing Company, Michigan City, Indiana. Its range was from 0 to 1 in. of water with graduations of 0.02 in. of water.

The calibration curve shown in Figure 28 was constructed by varying the number of perforations which were left open in the plenum. This gave varying pressures for the fan to work against and, since the perforated sheet is calibrated, this also tells the amount of air flowing.

With the calibration curve, all that is necessary for measuring the airflow from any pipe combination in a bin is to put the calibrated fan on the duct, as shown in Figure 27, drill a hole in the duct above the surface of the grain for a pressure tap, and take readings.

Figure 26. Components of the apparatus used to calibrate the fan

Figure 27. Calibrated fan shown attached to the vertical duct

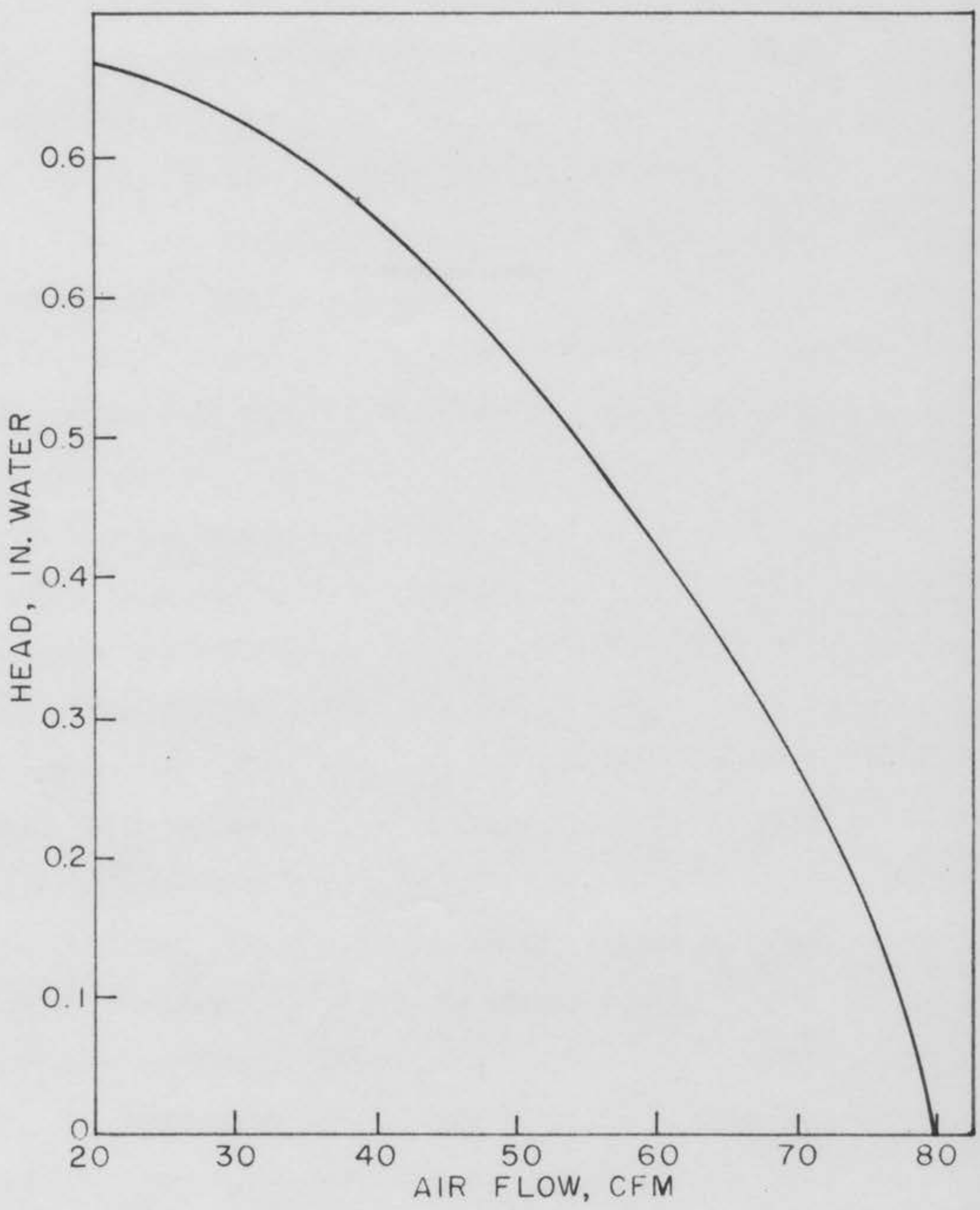


Figure 28. Fan-calibration curve

Results

The quantity of flow from systems having different lengths of perforated pipe are shown as points on the curve in Figure 29. It is to be noted that there is nothing which shows any difference in lengths of solid pipe. This is due to the fact that the difference in the amount of air being exhausted from systems at different depths is so small that no difference in amounts could be detected with this apparatus. Figure 29 also shows a plot of the calculated values from Table 4.

In the Analysis of the problem, the velocity head was not taken into account; therefore, since the quantity of air flowing is now known, the actual velocity head can be calculated. This velocity head represents the amount of change of pressure head from one end of the perforated pipe to the other. Thus, an average of the pressure heads at each end would give a better estimate than that made in the Analysis of the problem. The dotted curve in Figure 29 represents a plot of the calculated values corrected for velocity head.

The curve for measured values is extended to the zero length of perforated pipe, in which case all the air would be entering the open end of the solid pipe. No data are given for this value since it was due to some unsuccessful attempts to measure air flow on the systems used in the portion on winter operation. Results were unreliable and ranged

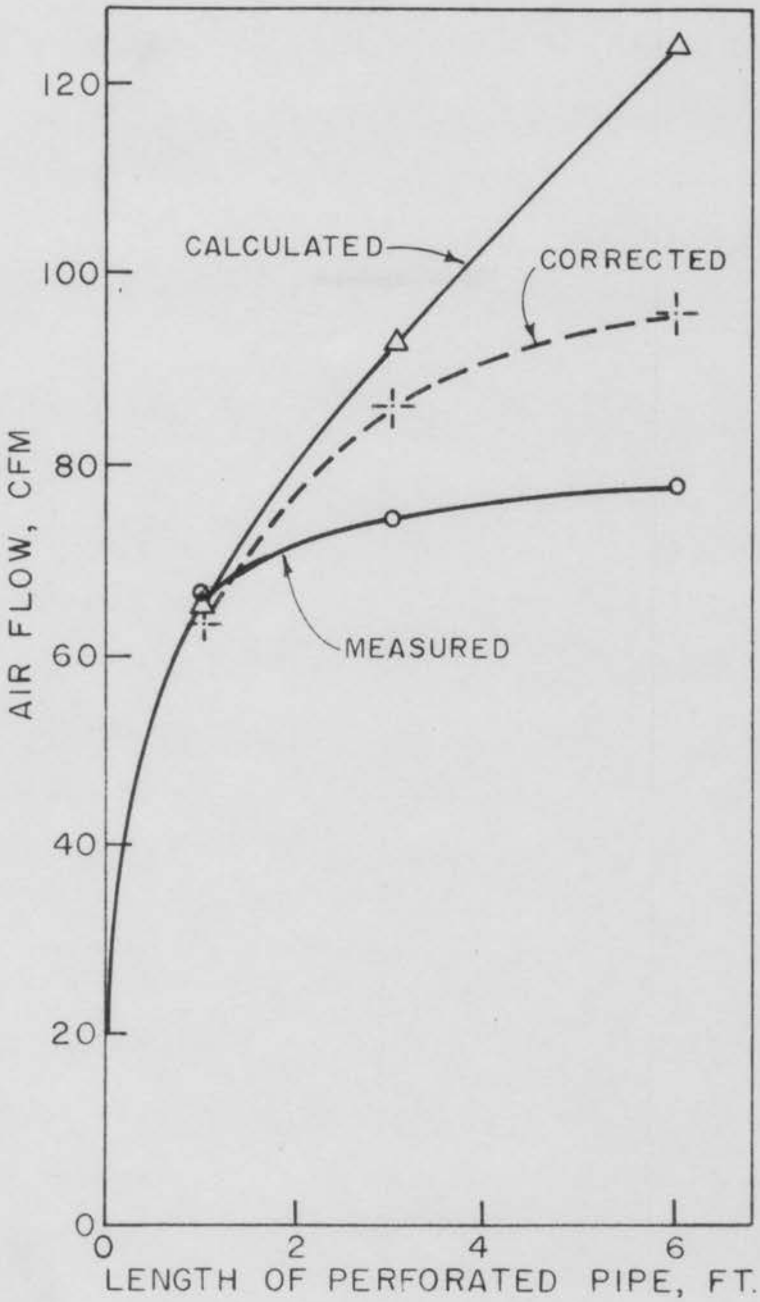


Figure 29. Plot of measured air flows with the calculated values obtained from Table 4. Calculated values are corrected for velocity pressure

from 12 to 21 cfm. This gave an expected range for the value when no perforated pipe was used, and the curve was extended to a point which would be included in this range.

Discussion of results

The discussion will confine itself primarily to discussion of Figure 29 and the significance of the curves presented there.

The difference in quantity of air flowing from the system having 3 ft and the one having 6 ft of perforated pipe is very small; nevertheless, there is some difference which indicates that there is no point where air ceases to enter. In other words, there appears to be a differential pressure acting along the entire length of the perforated pipe. The plot of the measured values of air flow indicates that the quantity of flow per unit area increases nearer the fan end of the perforated pipe. Thus, the 30-in. length determined from Figure 25 would not be an actual point, since there is air entering through the pipe beyond this point. The 30-in. length, then, indicates that this would be a point beyond which the quantity entering is not great enough to produce a change in grain temperature which could be measured with the apparatus used here.

It is impossible to determine with what accuracy the well-screen analogy can be applied to vertical-duct ventilators, since so few data are available which would serve to give a more definite answer.

The assumption was made that the rate of flow through the perforations per unit area was constant over the entire surface of the perforated pipe. This has since been shown to be an invalid assumption; however, the conclusions reached, i.e. that the change in pressure per unit depth becomes so small at distances of only a few feet from the perforated duct that they have no effect, is a valid conclusion. This is shown by the fact that there was no measurable difference in flow between systems having varying lengths of solid pipe.

It has been shown that the effect of the velocity head in these ducts produces an effect which is considerable. The resulting dotted curve in Figure 29, which represents the calculated values corrected for velocity head, is now within the limits of the accuracy of the gage used to measure the static pressure. As noted above, the gage was graduated in 0.02 in. water. This means that it could be read to only the nearest 0.01 in. water. The variation of $\pm$ 0.005 in. water from the values actually read would now give calculated values which would be within the limits of the accuracy of the gage.

SUGGESTED FUTURE STUDIES

The work reported in this manuscript has pointed up the need for further research in a number of things. This section is designed to enumerate what these needs are and is not meant to be a solution to problems but merely a guide for determining what some of the unsolved problems are. The needs for future studies are:

1. Determine the coefficient of contraction for perforated pipe when surrounded by small grains.
2. Determine whether Petersen's (5) analysis of well screens is applicable in the study of vertical-duct ventilators.
3. Study the effect of vertical-duct ventilators throughout an entire bin by use of a grid system of thermocouples. This should be carried out for at least a year.
4. Study the effect of varying the other components of the aeration system, as listed in Analysis of the problem.
5. Determine relationship between quantity of air flow and length of pipe for any given fan and duct system.

SUMMARY

The following are statements intended to summarize the results of this study.

1. The regions of a bin affected by vertical-duct ventilators vary throughout the year.
2. The length of solid pipe is more critical than that of the perforated pipe in affecting the depth of grain visibly affected.
3. The fan must be of adequate size to exhaust the air moving due to convection at the time this movement is at a maximum.
4. The maximum movement by convection occurs in February.
5. One-foot lengths of perforated pipe cause greater temperature gradients than longer lengths and should be avoided.
6. The measured effective length of perforated pipe was 30 in.
7. Amount of solid pipe has no measurable effect on quantity of air flow in bins usually found on farms.

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ACKNOWLEDGEMENTS

The author wishes to express his sincere appreciation to Professor W. V. Hukill, United States Department of Agriculture, who was in charge of the major work and whose suggestions and guidance have meant so much in preparing the research and writing this manuscript. Acknowledgements are also made to Professor Hobart Beresford, Head of the Department of Agricultural Engineering, for his encouragement in the effort.

The author also wishes to thank Mr. A. B. Groomes, manager of the Shipley Elevator Company, for making available the bins in which these tests were conducted, and to all others who have assisted in various ways with this work.